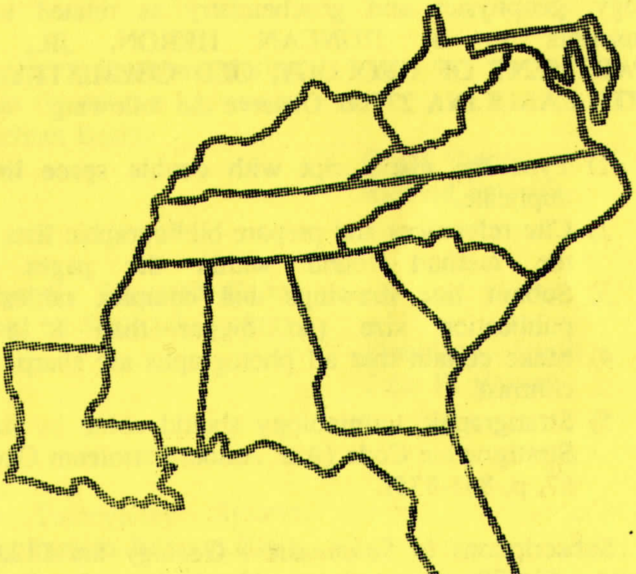
Southeastern Geology: Volume 30, No. 1
July 1989

Edited by: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY



PUBLISHED AT DUKE UNIVERSITY DURHAM, NORTH CAROLINA

VOL. 30, NO. 1 JULY 1989

SOUTHEASTERN GEOLOGY

PUBLISHED QUARTERLY

AT

DUKE UNIVERSITY

Editor in Chief:
S. Duncan Heron, Jr.

Managing Editor:
James W. Clarke

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SOUTHEASTERN GEOLOGY

Table of Contents

Vol. 30, No. 1

July 1989

LATE MISSISSIPPIAN DEPOSITIONAL PATTERNS IN THE NORTH-CENTRAL APPALACHIAN BASIN, AND THEIR IMPLICATIONS TO CHESTERIAN HIERARCHAL STRATIGRAPHY

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ABSTRACT

Upper Mississippian (Meramecian-Chesterian) strata of the north-central Appalachian Basin were deposited during repeated small-scale transgressive-regressive episodes that were superimposed upon larger-scale eustatic fluctuations. The first major transgressive episode is manifested by the Loyalhanna Limestone that unconformably overlies sandstones of the Burgoon Formation. Festoon cross-bedding that typifies the Loyalhanna throughout much of its extent is replaced in more nearshore areas by carbonate-shale couplets representing alternating marine and nonmarine conditions. Deposition of the Loyalhanna was followed by a short-lived transgressive event during which the purer, but areally restricted Deer Valley Limestone was deposited. Deer Valley deposition was followed by progradation of a wedge of red Mauch Chunk clastics herein termed the Savage Dam tongue over the previously deposited Loyalhanna and Deer Valley carbonates. Deposition within the Savage Dam tongue was characterized by the alternation of marine and nonmarine sedimentation. Marine deposits are most often white, well-sorted, fossiliferous, littoral sandstones whereas, the nonmarine rocks are mudcracked and root-mottled red mudstones, siltstones, and thin sandstones. Almost coincident with maximum geographic progradation of the Savage Dam clastic tongue is the initiation of a transgressive episode that culminated in the deposition of the Wymps Gap Limestone. Three major stillstand environments and their respective lithofacies include an open-shelf dark-gray wackestone, a carbonate shoal composed of coated grainstone, and a back-shoal open-circulation lagoon of siliciclastic-rich nodular-bedded wackestone. Red bed progradation concurrent with the Wymps Gap regression led to the deposition of an upper tongue of Mauch Chunk clastics. Throughout most of Pennsylvania this alluvial-plain type of sedimentation continued through the latest Mississippian. However, to the south (northern West Virginia and southwestern Pennsylvania) alluvial plain deposition is punctuated by two additional marine incursions. The first of these inundations produced the Glenray Limestone, and the second produced the geographically widespread Reynolds Limestone. Following Reynolds deposition alluvial plain sediments again prograded westward and southward.

Alternating transgressive and regressive Late Mississippian sedimentation in the north-central Appalachian Basin is a pattern similar to that described for the Illinois Basin, and northwestern Europe. In these areas the sedimentation patterns appear to have been the result of at least four scales of eustatic fluctuation.

INTRODUCTION

Upper Mississippian (Chesterian) strata of the north-central Appalachian Basin were deposited in two dissimilar depositional settings. In the central and southern portions of the basin, carbonates of the Greenbrier Group were deposited mainly under marine conditions (Figure 1), whereas, to the north and east, deposition of nonmarine red terrigenous sediments took place (Mauch Chunk Formation). Between these two disparate depositional settings, was an area where, as a result of an intimate interplay of eustatic sea level changes, subsidence, and sediment influx, marine carbonates intertongue with predominately nonmarine red clastics. Rock units in this zone of intertonguing consist, in ascending order, of the Loyalhanna and Deer Valley Limestones, the Savage Dam clastic tongue, the Wymps Gap Limestone, the Lillydale Shale, the Glenray Limestone, the Bickett Shale, the Reynolds Limestone, and an overlying tongue of red clastics (Upper Mauch Chunk of Hoque, 1968).

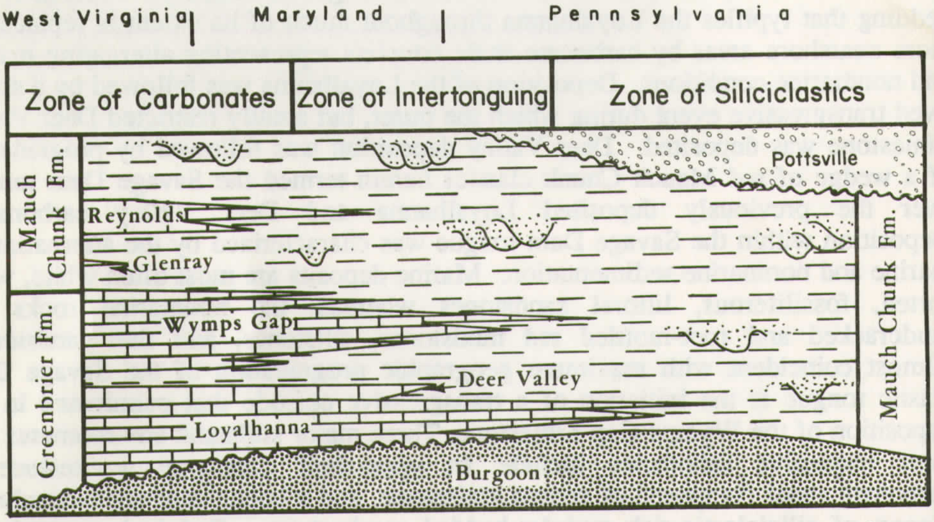

Figure 1. Generalized facies relationships of Chesterian strata in the north-central Appalachian Basin illustrating major carbonate tongues and their lateral relationships (no scale implied).

Although there have been studies of this stratigraphic interval (Haney, 1963; Hoque, 1968; Adams, 1970; Busanus, 1974; Presley, 1979), these have largely been confined to single units of very localized geographic areas. Consequently, an integrated depositional hypothesis for this stratigraphic section has been lacking. The goals of this paper are to: 1) integrate, into a synthesis of depositional history, several of the more significant previous studies with data collected from 28 measured sections of Meramecian and Chesterian strata from portions of Pennsylvania, Maryland, and West Virginia (see Brezinski, 1984a, p. 96-113 for measured sections) (Figure 2), and 2) to provide a hierarchy of transgressive and regressive units and their possible use in correlation within the Meramecian-Chesterian strata of the Appalachian Basin.

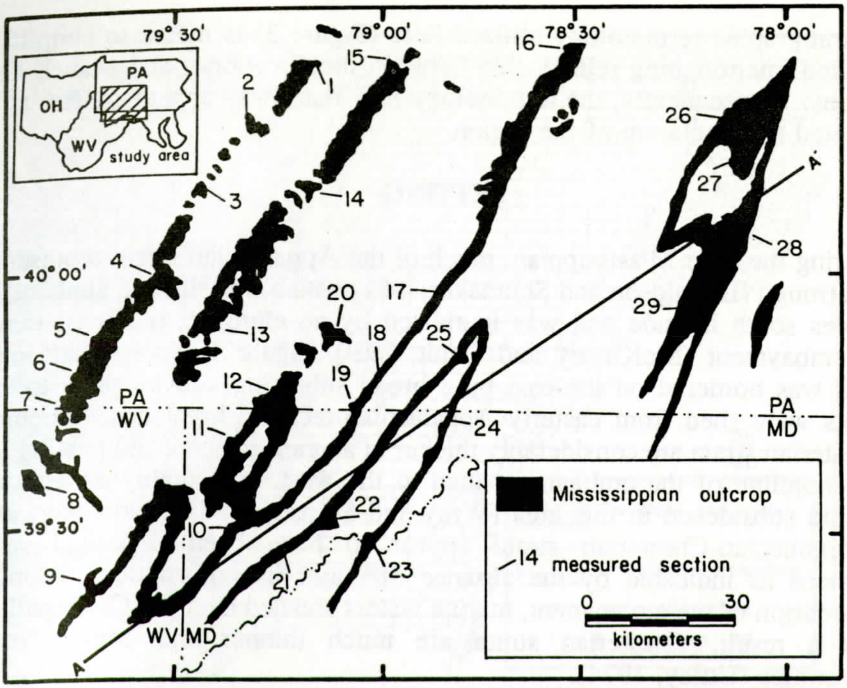

Figure 2. Location map of measured sections and distribution of Mississippian outcrop (black). Cross-section line A-A' roughly equivalent to line of section illustrated in Figure 1.

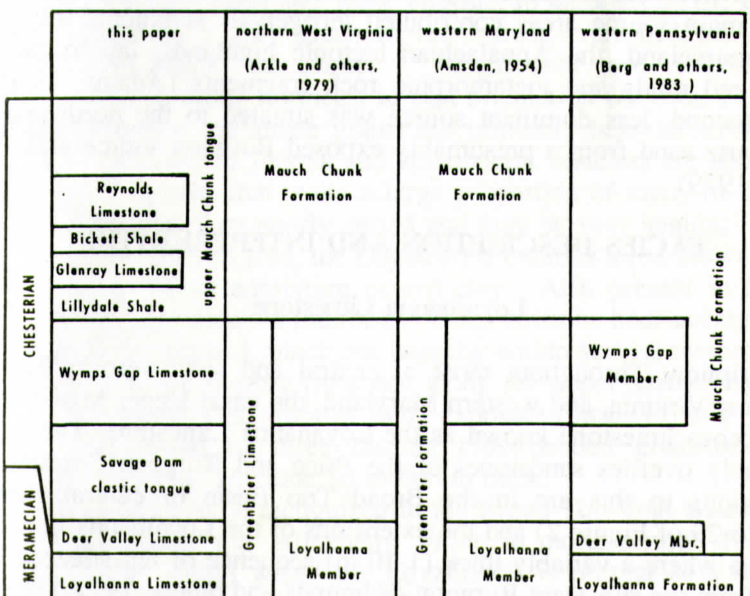

Figure 3. Correlation diagram illustrating current stratigraphic nomenclature for Upper Mississippian strata of western Pennsylvania, Maryland, and northern West Virginia and terminology used in this paper.

Stratigraphic terminology utilized here (Figure 3) is meant to simplify the complicated intertonguing relationship between the Greenbrier and Mauch Chunk Formations. Consequently, the terminology may not alway appear consistent with the accepted nomenclature of the region.

SETTING

During the Late Mississippian, much of the Appalachian Basin represented a foreland trough (Donaldson and Shumaker, 1981) which was situated at about 10 to 15 degrees south latitude and was inundated by an elongate, northeast trending marine embayment (McKinney and Gault, 1980, Figure 1; Scotese and others, 1979). It was bordered on the east by a broad subsiding alluvial plain to which sediments were shed from easterly Appalachian tectonic highlands. Meramecian and Chesterian strata are considerably thicker in an area adjacent and parallel to the eastern shoreline of the embayment than to the west, presumably as a result of more rapid subsidence in this area (Wray and Smosna, 1982). Moreover, in this area Meramecian-Chesterian strata appear to have been deposited without interruptions as indicated by the absence of major unconformities. Along the western margin of the embayment, marine waters shoaled over the Cincinnati Arch and, as a result, Chesterian strata are much thinner and contain several unconformities (Uttley, 1974).

Throughout the Late Mississippian the Mauch Chunk clastic wedge progressively prograded to the west and southwest and was interrupted only periodically by marine incursions. Consequently, the base of the Mauch Chunk clastic wedge becomes progressively older to the east and northeast.

Two main source areas contributed terrigenous sediments into the basin. The main sourceland, the Appalachian tectonic highlands, lay to the east and contributed red muds and metamorphic rock fragments (Adams, 1970; Hoque, 1968). A second, less dominant source was situated to the north and supplied recycled quartz sand from a presumably exposed Burgoon source area (Edmunds and others, 1979).

FACIES DESCRIPTION AND INTERPRETATION

Loyalhanna Limestone

Description: Throughout most of central and southwestern Pennsylvania, northern West Virginia, and western Maryland, the basal Upper Mississippian unit is an arenaceous limestone known as the Loyahanna Limestone. The Loyalhanna unconformably overlies sandstones of the Price and Burgoon Formations. The only exceptions to this are in the Broad Top Basin of central Pennsylvania (localities 26-29 of Figure 2) and the extensions of the Loyalhanna in northeastern Pennsylvania where a variably thick (1-10 m) sequence of red siltstone and shale separate it from the subjacent Burgoon (Edmunds and others, 1979; Gallagher and Parks, 1983).

Over its known extent two generalized lithofacies comprise the Loyalhanna Limestone (Figure 4). What might be considered as "typical" Loyalhanna is present throughout the Appalachian Plateaus Province of southwestern Penn-

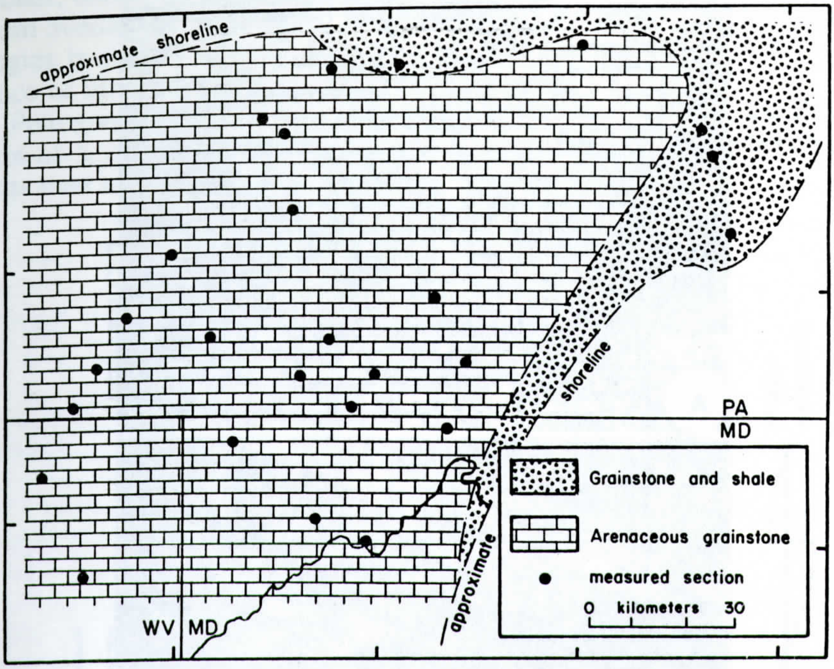

Figure 4. Lithofacies distribution within the Loyalhanna Limestone at maximum transgression, from Brezinski (1984a).

sylvania and adjacent Maryland and West Virginia. In these areas, the Loyalhanna can be characterized as a gray green to red brown, cross-bedded, arenaceous grainstone to calcareous sandstone. Megafossils are notably absent. Paleocurrents exhibit a strong northeast to east orientation (Adams, 1970; Hoque, 1975). Petrographically, carbonate grains are primarily peloids, however, ooids and fossil grains (endothyrid forams and echinoderm ossicles) are also common. Quartz sand and silt grains that make a large proportion of many of the foresets vary from moderately-well to poorly sorted and may be very angular. Along the eastern portion of its outcrop area, the Loyalhanna exhibits a red brown coloration that is the result of minor admixture of red clay. Also present in the eastern outcrop area are thin red siltstone interbeds. These siltstone beds average 30 cm in thickness (but may be thicker), pinch out laterally within several meters, possess a gradational base, and are sharply truncated along the upper surface by overlying cross-bed foresets. In the southernmost study exposure (locality 9 of Figure 2) the Loyalhanna is comprised of three distinct cross-bedded grainstone intervals separated by tan dolomitic siltstone 30 to 60 cm thick.

A second facies can be recognized in the Broad Top Coal Basin of central Pennsylvania and along the Allegheny Front in north-central Pennsylvania (Gallagher and Parks, 1983) where the Loyalhanna is present as a sequence of interbedded cross-bedded grainstone and calcareous red siltstone and shale (Figures 5B,C, 6). In the Broad Top Basin, this interval has been termed the Trough Creek Limestone (Reger, 1927; Adams, 1970; Lentz and others, 1986). The Trough Creek facies of the Loyalhanna consists of a scour-based, cross-bedded carbonate unit 1-3 m thick that grades upward into red, thin interbedded, argillaceous

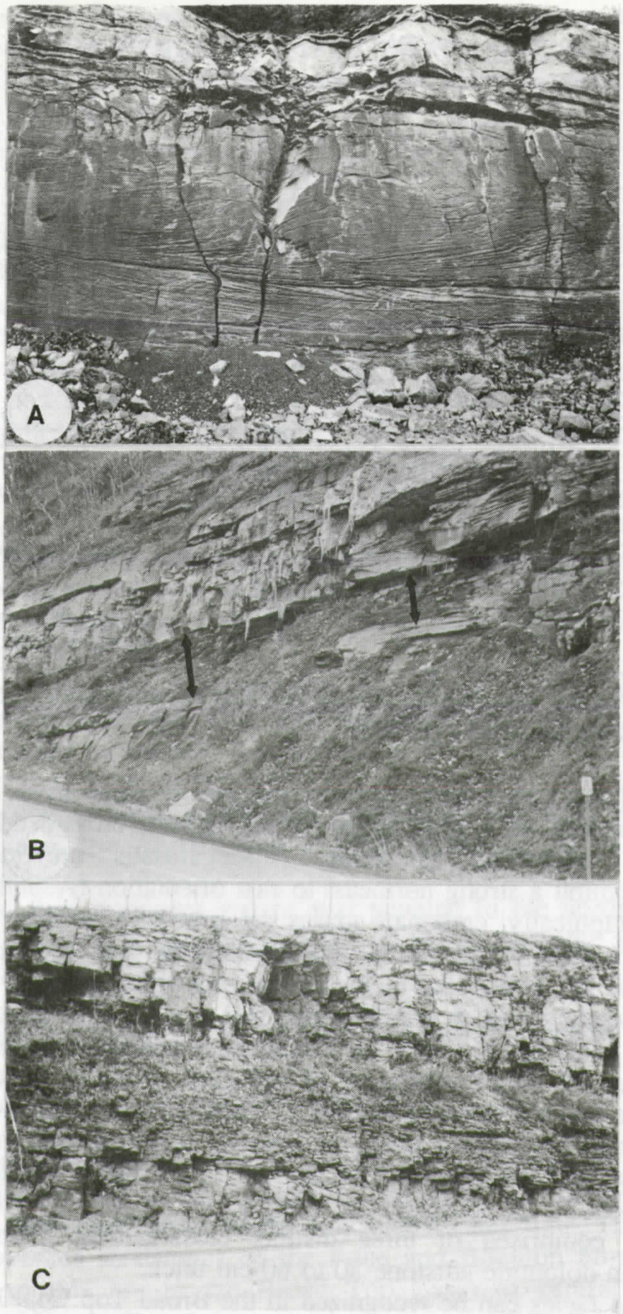

Figure 5. Lithofacies of the Loyalhanna, A, festoon-cross-bedded, arenaceous grainstone facies of locality 12 illustrative of the Loyalhanna throughout most of the plateau region (light-colored Deer Valley Limestone overlying the cross-bedded Loyalhanna is 3 m thick), B, siltstone lense (arrows) separating upper and lower ledges of the Loyalhanna (locality 15), C, interbedded grainstone and shale facies. Thin-bedded lithosome near middle of exposure is 3.5 m thick

limestones, containing a fenestral fabric, and calcareous siltstone and shale. This is in turn overlain by mudcracked and root-mottled red siltstone. This sequence of lithologies is sharply overlain by a second cross-bedded carbonate unit, and the sequence of lithologies is repeated (Figure 6).

Petrographically, the thicker Loyalhanna carbonate beds of the Broad Top consists of a peloidal grainstone with quartz sand and silt in noticeably lesser amounts than in "typical" Loyalhanna.

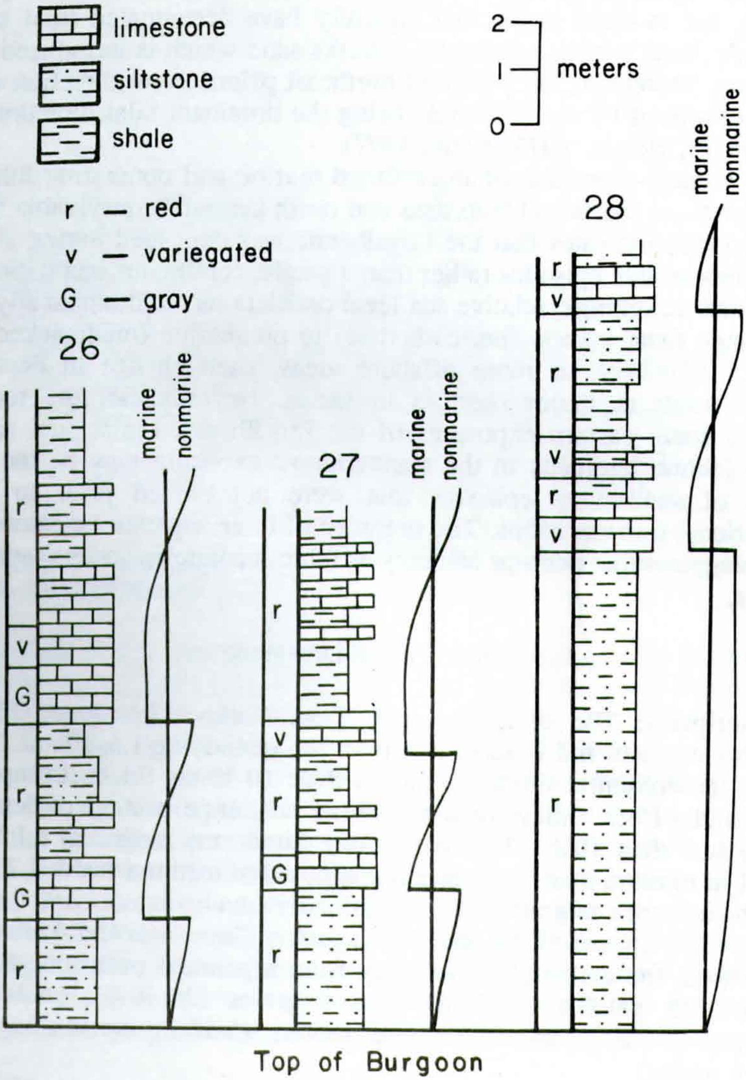

Figure 6. Vertical and lateral lithologic variations and interpreted sea level curve for the Loyalhanna Limestone (Trough Creek facies) within the Broad Top Basin of central Pennsylvania (column numbers correspond to numbers of localities in Figure 2).

Interpretation: Adams (1970) proposed that the Loyalhanna represents a shallow sand-wave complex. The festoon cross-bedding, diagnostic of the Loyalhanna of southwestern Pennsylvania and adjacent West Virginia and Maryland, resulted from submarine sand-wave migration. Modern analogues may be submarine sand-wave complexes in the North Sea (McCave and Langhorne, 1982) or Long Island Sound (Bokumiewicz and others, 1977). Walker (1979) has shown that modern examples of submarine sand-wave complexes are situated in estuarine regions of shallow marine shelves. Such esturine shelves, by virtue of their shape, act as sand sinks, and typically have accentuated tidal exchanges. Consequently, tidal motion constantly reworks sand which is introduced into such environments. Moreover, the preferred northeast paleocurrent direction appears to have been produced by the flood tide being the dominant tidal direction (Adams, 1970, figure 13; Hoque, 1975: Klein, 1977).

The vertical repetition of interbedded marine and nonmarine lithologies in the Loyalhanna of the Broad Top area and north-central Pennsylvania (Gallagher and Parks, 1983) indicates that the Loyalhanna was deposited during at least two separate transgressive episodes rather than a single, continuous inundation (Figures 5C, 6). In paralic settings, relative sea level oscillations are dramatically exhibited by the change from marine (i.e. carbonate) to nonmarine (mudcracked siltstone) deposition. However, in more offshore areas, each change in depth did not necessarily result in major changes in facies. Nevertheless, the red siltstone interbeds in some eastern exposures of the Loyalhanna Limestone, and the tan dolomite siltstone interbeds in the southernmost exposure may be the preserved remanents of shallowing episodes that were not eroded prior to or during intraformational transgressions. The presence of three separate limestone ledges at locality 9 suggests that perhaps as many as three separate episodes may be present in this area.

Deer Valley Limestone

Description: The relatively pure Deer Valley Limestone (Flint, 1965) conformably overlies and is separated from the underlying Loyalhanna Limestone by either a tan dolomitic siltstone or a red shale 10-15 cm thick. Compared to the Loyalhanna, the Deer Valley contains a much smaller percentage of detrital quartz, commonly less then 10%. The Deer Valley Limestone ranges in thickness from less than 1 m to more than 11 m, and is composed of medium-bedded, light-gray to gray green packstone to grainstone. Megafossils are uncommon, and those that are present typically consist of the brachiopod genera *Composita* and *Anthracospirifer*. In thin section, the carbonate strata vary from a peloidal packstone to an oolitic grainstone with peloids (15-20%), coated grains (20-40%), ooids (10-25%), echinoderms (5-20%), and endothyrid forams (5-10%) constituting the main framework grains.

The uppermost strata (0.3-1.0 m) of each exposure commonly consist of interbedded red and green, root-mottled and mudcracked siltstone and shale and red silty packstone exhibiting cross-laminations. These lithologies intercalate with and grade into clastics of the overlying Savage Dam clastic tongue. Along the northern periphery of its distribution, the Deer Valley is present as a cross-bedded, arenaceous, highly fossiliferous grainstone similar to the underlying

Loyalhanna. However, the Deer Valley can be distinguished from the Loyalhanna by the abundance of brachiopods in the former. Near the southern margin of the area studied, the Deer Valley consists of dark-gray argillaceous limestone containing crinoid ossicles and brachiopod fragments.

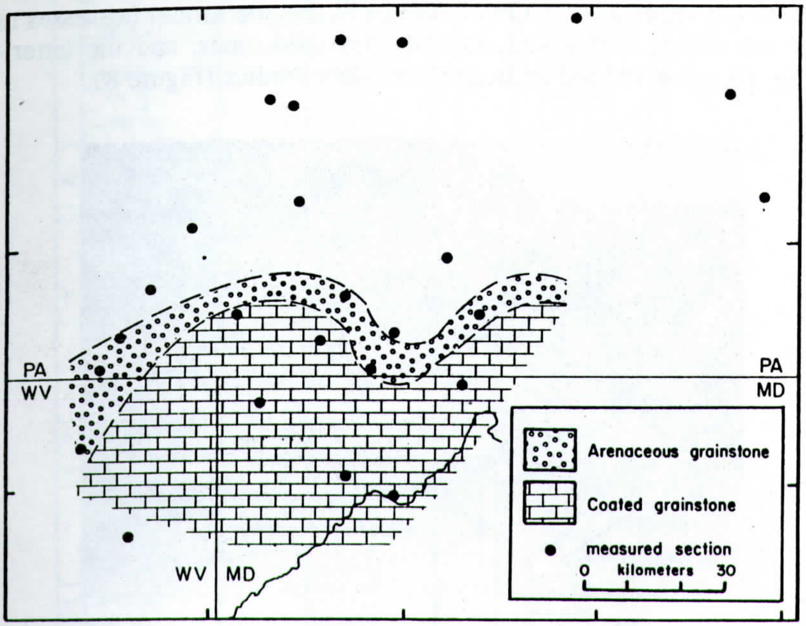

Figure 7. Lithofacies distributions within the Deer Valley Limestone at maximum transgression, from Brezinski (1984a).

Interpretation: The Deer Valley Limestone represents a single minor marine incursion, which trangressed only a short distance to the northeast from the main marine body located to the southwest (Figure 7). Throughout most of its lateral extent, the Deer Valley was deposited in a shallow, agitated shoal environment as indicated by the coated grains and ooids. The paucity of megafauna might be explained by the unstable substrate due to shifting sands. Along the northern periphery of the Deer Valley embayment, the fossiliferous, arenaceous grainstone represents wave-reworked shoreline deposits. Farther to the southwest (locality 21, Figure 2), deepers water are reflected by the facies change of Deer Valley grainstones into fossiliferous dark-gray argillaceous wackestones (Adams, 1970). Shoaling facies of the Deer Valley are represented by caprock lithology of interbedded root-mottled and mudcracked siltstone and shale and red packstone. These strata indicate progradation of the Mauch Chunk shoreline to the west.

Savage Dam Clastic Tongue

Description: Overlying the Deer Valley Limestone (and where the Deer Valley is absent, the Loyalhanna Limestone) is a tongue of terrigenous sediments which thins from 200 m in the Broad Top area of Pennsylvania, and pinches out just west of the Chestnut Ridge Anticline (localities 1-8, Figure 2). Hoque (1968) and Brezinski (1984a) termed this interval the "clastic interval". This interval will herein be termed the Savage Dam clastic interval for its exposure in Garrett County, Maryland (locality 22, Figure 2, and Figure 8 and 9). It can only be recognized where separated from the upper wedge of Mauch Chunk clastics by the intervening Wymps Gap Limestone. Compositionally, the Savage Dam tongue differs from the upper Mauch Chunk tongue in that the former possesses numerous thin (1-2 m) white, well-sorted, fossiliferous sandstones, and the latter contains thick (15+ m) cross-bedded lenticular sandstone bodies (Figure 8).

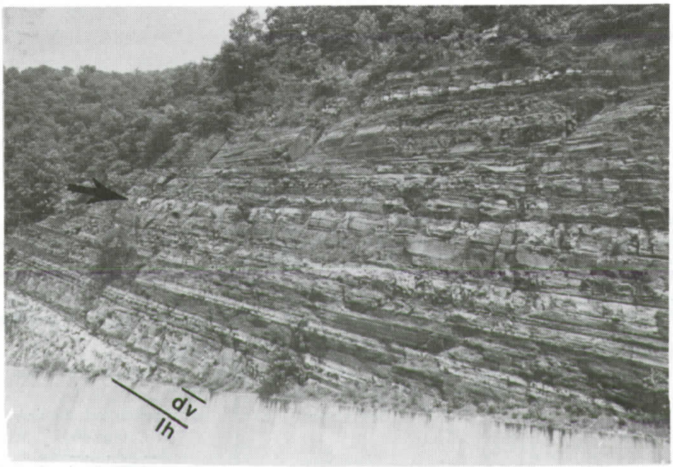

Figure 8. Character of variation in lithology within the Savage Dam clastic tongue of the Mauch Chunk at locality 22 (note planar-bedded white sandstones near middle of exposure [at arrow]). Upper portion of the Loyalhanna (lh) and Deer Valley (dv) Limestones are light-colored units in lower left. Deer Valley Limestone is 3 m thick.

The Savage Dam tongue is characterized by white sandstones interbedded with gray green and red brown siltstone, shale, and sandstones (Figure 8 and 9). White sandstones contain carbonate clasts, brachiopod fragments, are well-sorted, and display a sheet-like geometry, and basal scour contacts (Hoque, 1968). They commonly grade up-section into the gray green, sandy siltstone and shale and finally into red brown siltstone, sandstone, and shale. The red shale and siltstone intervals are commonly root-mottled and pervasively mudcracked. The red-brown siltstone and shale are overlain by similar sequences with basal white sandstone. The sequence is repeated up-section as many as 6 times. However, where the superjacent Wymps Gap is present, the white sandstone portion of the repeated sequences is progressively replaced by fossiliferous gray green and red brown shale containing brachiopods, bivalves, and corals. Faunal diversity within succeeding marine intervals progressively increases up-section.

Interpretation: The lower tongue of the Mauch Chunk appears to have been deposited during several minor transgressions of sea level. The shallowing, which terminated deposition of the Deer Valley was accompanied by predominately

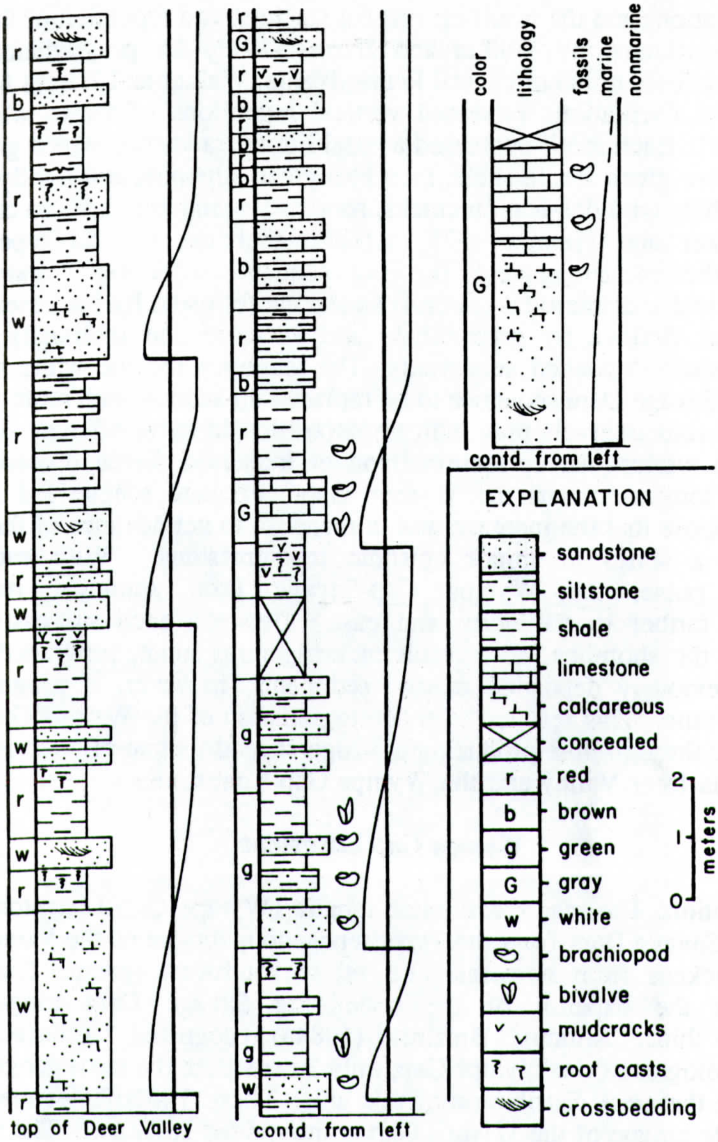

Figure 9. Vertical lithologic variation in the Savage Dam tongue of the Mauch Chunk at locality 22, with interpreted sea level curves.

terrestrial deposition of red terrigenous sediments on a low-relief alluvial plain as the shoreline prograded westward and southward (Edmunds and others, 1979; Brezinski, 1984a). Following the shoaling of the Deer Valley, a minor sea level rise resulted in the inundation of the subaerial plain and intertidal or shallow subtidal deposition of a white sandstone took place. Terrigenous sediment quickly overwhelmed the marine conditions, and aggradation and progradation into a subaerial plain was rapidly accomplished. Subsequently, another minor transgression produced repetition of the lithologies. Analogous scales of minor sea level oscillations and the resulting vertical stacking and repetition of lithologies have been documented by Walker and Harms (1971) for progradation of the Devonian Catskill shoreline of central Pennsylvania. Walker and Harms found that minor sea level oscillations produced vertical repetitions of facies which they termed "motifs". Each motif possessed a basal littoral sandstone which graded up-section into olive-green fissile shale, then into green siltstone, and finally into red siltstone and shale with dessication cracks, root-traces, and zones of tan calcareous nodules. Walker and Harms (1971) inferred that the vertical repetition of lithologies indicated an upward shoaling sequence. A rapid transgression deposited subtidal and intertidal (littoral) sandstone followed by increased rates of sediment influx defined by green shale and siltstone and ultimately into red siltstone and shale deposited subaerially. The tendency for the white sandstone portion of the Savage Dam sequence to be replaced up-section with more shaly and highly fossiliferous intervals may indicate deposition in more offshore or slightly deeper marine waters. An up-section trend of increased faunal diversity in the Savage Dam tongue toward the Wymps Gap carbonate tongue led Brezinski (1984c) to propose that the increase was in response to net advance of the Wymps Gap sea via a series of minor episodic transgressions. With each minor transgressive pulse, the Wymps Gap-Savage Dam shoreline retrograded progressively farther to the north and east. Between each successive minor transgression, the shoreline, as a result of terrigenous input, prograded seaward back over previously deposited marine sediments; however, it prograded less seaward each time. This resulted in net retrogradation of the Wymps Gap-Savage Dam shoreline through time producing a wedge-shaped tongue of clastics between the Loyalhanna-Deer Valley and the Wymps Gap Limestones.

Wymps Gap Limestone

Description: The major carbonate tongue (Wymps Gap Limestone) which separates the Savage Dam from the upper terrigenous tongue of the Mauch Chunk Formation thickens from northeast (1.5 m) to southwest (greater than 20 m), apparently at the expense of the underlying Savage Dam tongue which concomitantly thins. Although Brezinski (1984a) recognized 7 lithofacies in the carbonate lithologies of the Wymps Gap, only 3 constitute the most geographically widespread in the areal distribution of this unit. These 3 lithofacies make up the main carbonate tongue of the Wymps Gap at interpreted stillstand. The remaining 4 lithofacies are typically quite thin and localized. Consequently, only the 3 major lithofacies will be discussed here.

Where the Wymps Gap is thin (1-6 m) it is composed of a gray green to red brown, variegated, argillaceous, nodular-bedded, wackestone to packstone (Figure 10A). The nodular-bedding is caused by thin interbeds of shale surrounding purer carbonate sedimentary boudins (3-10 cm in diameter). Very-thin cross-laminations, graded-bedding, and hummocky cross-stratification are common throughout. In thin section productid brachiopod valves and spines (10-25%) and fenestrate and ramose bryozoans (5-30%) are the most common constituent grains.

To the southwest where the Wymps Gap is thicker (8-20 m), it is composed of medium-bedded, dark-gray to black, argillaceous, fetid wackestone (Figure 10C). In polished slabs, limestones exhibit thorough bioturbation. In thin

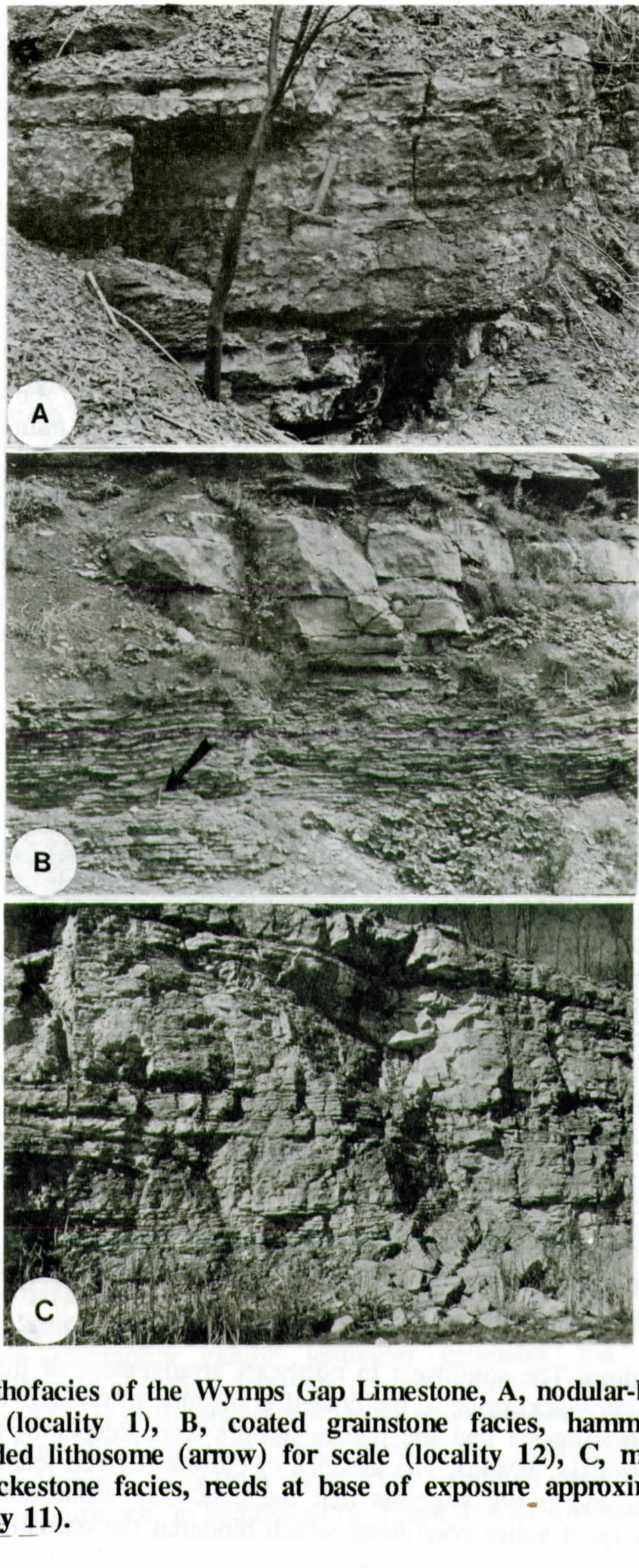

Figure 10. Lithofacies of the Wymps Gap Limestone, A, nodular-bedded wackestone facies (locality 1), B, coated grainstone facies, hammer within the rhythmic-bedded lithosome (arrow) for scale (locality 12), C, medium-bedded, dark-gray wackestone facies, reeds at base of exposure approximately 2 m in height (locality 11).

section the predominant carbonate grains are brachiopod valves (20-35%), echinoderms (5-25%), and endothyrid forams (3-8%). A large amount of the carbonate material (30-70%) is silt-size and appears to be skeletal in origin, but further identification was impossible. Many of the larger carbonate grains have been replaced, to some degree, by pyrite. Common megafossils include the brachiopods *Diaphragmus*, *Orthotetes*, *Martinia*, *Cleiothyridina*, and *Inflatia*, plus disarticulated pelmatozoan ossicles. Cross-bedding, graded-bedding, storm deposits, and indications of scouring are notably absent.

The third lithofacies is present in a narrow band which separates the nodular-bedded facies from the dark-gray facies. In this band, the Wymps Gap ranges in thickness from 3.0-7.0 m and is composed of a light-gray, locally cross-bedded, well-sorted, coated grainstone (Figure 10B). In thin section, the predominant constituent grains are peloids (40-50%) which exhibit single to multiple layers of micrite coating. Also common are grapestone aggregates (15-20%) and locally, well-developed ooids (2-50%). Unlike adjacent lithofacies, megafauna in this facies is sparse and generally consists of disarticulated valves of the brachiopod *Anthracospirifer*. Microfossils consist of abundant (5-15%) endothyrid forams and the dasyclad alga *Atractyliopsis* (2-5%).

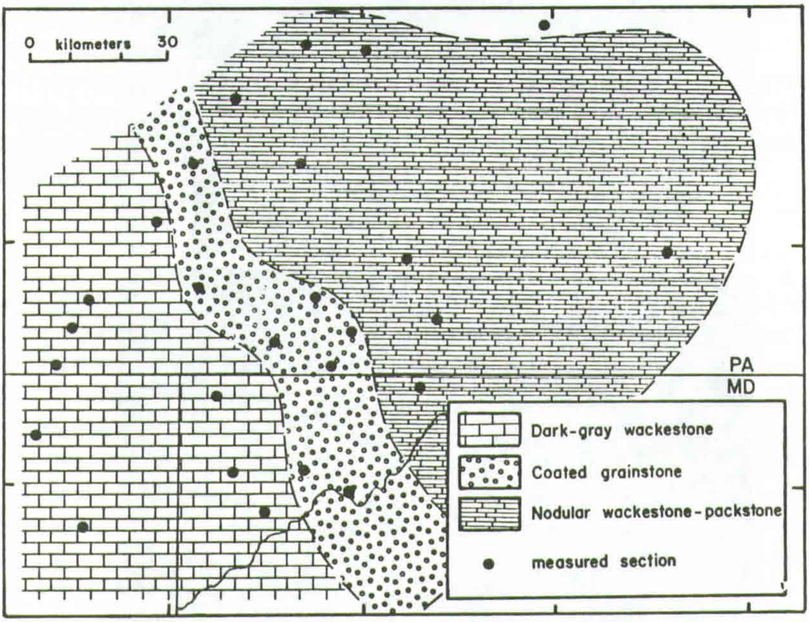

Figure 11. Lithofacies distribution within the Wymps Gap Limestone at maximum trangression, from Brezinski (1984a).

Interpretation: The southwest to northeast arrangement of lithofacies belts from the dark-gray wackestone to the coated grainstone to nodular-wackestone of the Wymps Gap suggests that the marine waters were deeper to the southwest (Figure 11) (Brezinski, 1984a). The absence of current-derived features, abundant organic content, and pyrite suggests that the dark-gray wackestone facies was deposited under quiet water conditions which hindered the oxidation of organics and aided the development of authigenic pyrite below the sediment/water interface. The fragmentation and comminution of fossil remains is likely the result of deposit-feeding organisms that ingested organic detritus. Such an environment would presumably be in waters deeper than average storm wave-base inasmuch as current indicators and storm deposits are general absent. Based on lateral facies relationships Brezinski (1984a, p.38) interpreted this lithology to have been deposited in 40 to 50 m of water. If this depth estimate is correct, this facies of the Wymps Gap represents the deepest water depth attained in this part of the Appalachian Basin during the Chesterian. Conversely, the coated grainstone lithofacies appears to have been deposited in shallower agitated waters. The cross-bedding and coated or oolitic grains suggest that the sands were at least intermittently mobile. The abundance of endothyrid forams is analogous to the Salem Limestone of Indiana which Donahue (1967) interpreted as having formed on a carbonate sand shoal.

The cross-laminations and graded-bedding suggest that the nodular wackestone lithofacies was similarly deposited in shallow waters. The abundance of fine-grained siliciclastic and carbonate muds suggests that the environment was low energy and proximal to the terrigenous source. Brezinski (1984a) interpreted this facies as having formed in a shallow water lagoon leeward of the coated grain or oolite shoals.

Upper Clastic Tongue of the Mauch Chunk

Description: Overlying the Wymps Gap Limestone throughout most of southwestern Pennsylvania and adjacent Maryland is a sequence of red sandstone, siltstone, and shale termed upper Mauch Chunk by Hoque (1968) and Brezinski (1984a) (simply Mauch Chunk Formation of West Virginia and Maryland). Although this nonmarine sequence extends over most of Pennsylvania and Maryland, two thin carbonate tongues punctuate the section in northern West Virginia and southwesternmost Pennsylvania.

The lower of these tongues (known in northern West Virginia as the Glenray Limestone (Busanus, 1974)) is thin (0.2-3 m) and is commonly situated less than 2 m above the top of the Wymps Gap Limestone. Separating the two limestones is laminated fossiliferous gray green shale with thin (1-3 cm) wackestone interbeds. The fossils of the wackestone beds are commonly fragmentary, disarticulated, and platy fragments are often imbricated. The Glenray is thick-bedded and light-gray in color. In thin section, it is composed of well-sorted peloids and echinoderm ossicles. In northern and eastern exposures (localities 5,6,10, Figure 2), the Glenray consists of two ledges of argillaceous wackestone separated by thinly cross-laminated calcareous shale (Figure 12, column 5). Overlying the Glenray Limestone is the Bickett Shale (Busanus (1974), a 4-9 m interval of interbedded red brown to green gray shale, siltstone, and thin sandstones. Sandstones in the Bickett Shale commonly exhibit lenticular geometry and a fining-upward character. Siltstone and shale intervals contain abundant root-traces. Farther to the south, the Bickett Shale grades into shales that contain marine fossils (Presley, 1979). The Reynolds Limestone, which overlies the Bickett Shale over much of northern West Virginia, thins from about 10 m, in central West Virginia, to 1 m at its northern occurrence in southwestern Pennsylvania (locality 5, Figure 2).

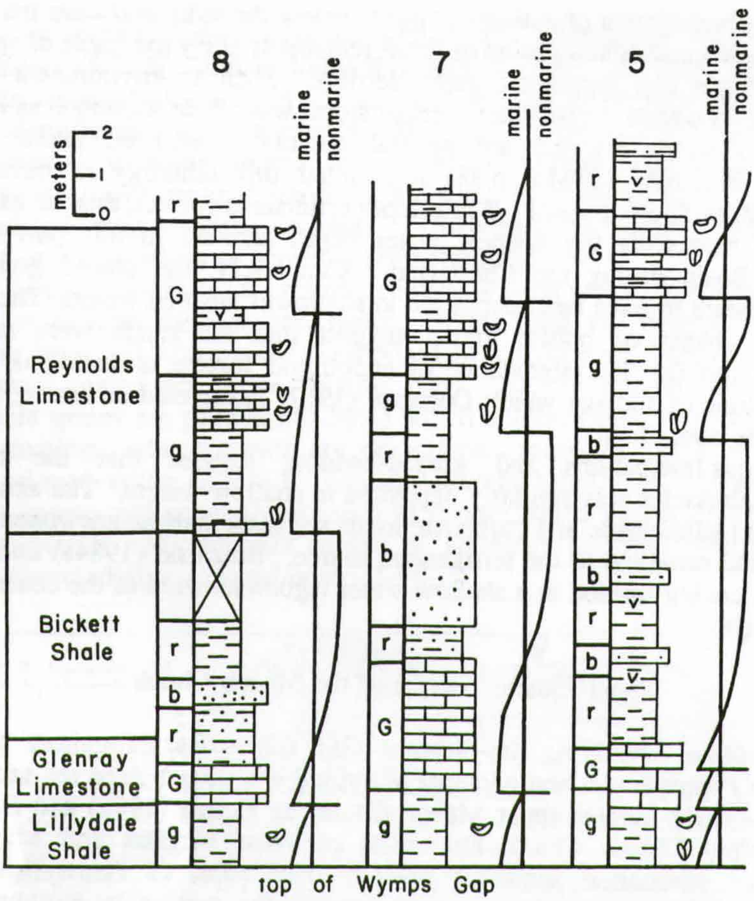

Figure 12. Vertical and lateral facies distributions for the interval from the top of the Wymps Gap Limestone through the Reynolds Limestone and interpreted sea level curves, (see Figure 9 for explanation of symbols).

Typically occurring as two limestone ledges separated by a thin (10 cm) shaly interval, the Reynolds consists of a medium to dark-gray fossiliferous, fetid, wackestone to packstone. The upper surface of the upper limestone ledge commonly exhibits scour pockets filled with disarticulated brachiopod and gastropod shells (Busanus, 1974). Common faunal components include the brachiopods *Orthotetes*, *Diaphragmus*, *Anthracospirifer*, and *Composita*. The shaly interval which pervasively separates the two limestone ledges contains a laterally extensive horizon of desiccation cracks (Busanus, 1974).

Petrographically, the Reynolds can be classified as an argillaceous wackestone in which many of the fossil fragments have been partially replaced by pyrite. Much of the shelly carbonate material has been reduced to silt-size grains. Polished slabs illustrate that the sediment has been thoroughly bioturbated. With the exception of the scour pockets present on the upper surface of the top ledge, indications of current activity are absent.

Overlying the Reynolds in northern West Virginia, and coeval with the Glenray-Reynolds interval in much of Pennsylvania and Maryland, are terrestrial

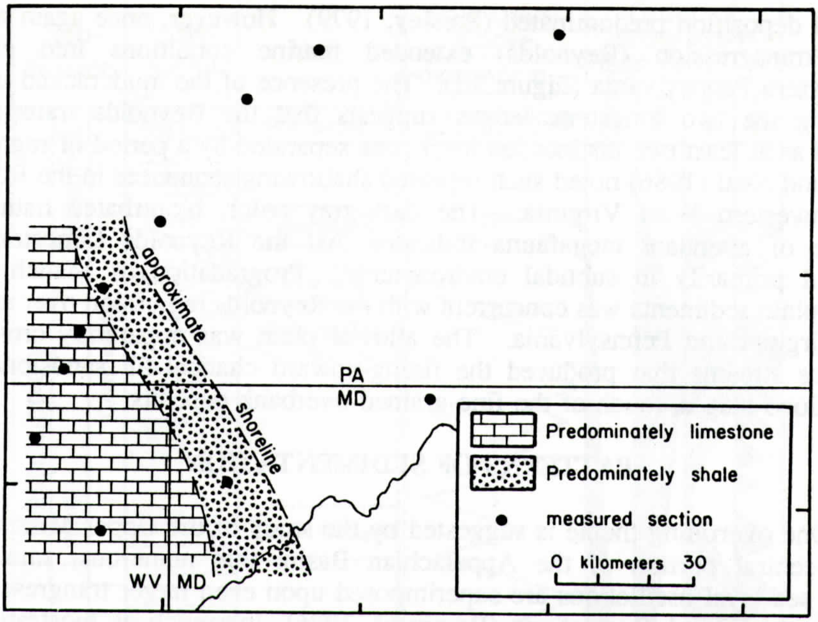

Figure 13. Lithofacies distribution within the Reynolds Limestone at maximum transgression, from Brezinski, 1984a.

deposits equivalent to the Upper Mauch Chunk of Hoque (1968). In these areas, the Mauch Chunk consists of predominately red to red brown, locally green, silty shale, siltstone, and sandstone. The sandstone units are commonly multi-stacked, quite thick (10+ m), locally exhibiting epsilon cross-bedding, and fining-upward (Meckel, 1970; Presley, 1979). Unlike the thin, well-sorted, sheet-like, white sandstone units present in the Savage Dam tongue, those in the upper tongue commonly display a lenticular geometry, erosional bases, shale pebble lags, trough cross-bedding, and are compositionally subgraywackes (Hoque, 1968; Meckel, 1970).

Interpretation: The Mauch Chunk sequence overlying the Wymps Gap represents an overall regressive episode. Progradation was interrupted, at least to the southwest, by thin and areally restricted (compared to the Wymps Gap or Loyalhanna) marine incursions. These incursions are represented by the Glenray and Reynolds Limestones. The upper tongue of the Mauch Chunk was deposited in an alluvial plain environment (Meckel, 1970; Presley, 1979) with migrating meandering fluvial channels that deposited multi-stacked lenticular sandstones (Hoque, 1968). The red, fine-grained terrigenous sediments represent overbank and lacustrine deposits (Meckel, 1970).

The Glenray Limestone was deposited during a minor marine transgression that followed the Wymps Gap regression. The Glenray appears to have been deposited in a shallow subtidal or intertidal carbonate sand environment. Regression of the Glenray sea was accompanied by progradation of the terrigenous shoreline of the Bickett Shale. In northern West Virginia, this sequence is nonmarine, but farther to the south, nearer the main body of the Chesterian seaway, intertidal deposition predominated (Presley, 1979). However, once again another marine transgression (Reynolds) extended marine conditions into extreme southwestern Pennsylvania (Figure 13). The presence of the mudcracked interval separating the two limestone ledges suggests that the Reynolds transgression occurred as at least two distinct sea level rises separated by a period of regression. Corbitt and Neal (1986) noted such repeated shallowing sequences in the Reynolds of southwestern West Virginia. The dark-gray color, bioturbated nature and presence of abundant megafauna indicates that the Reynolds Limestone was deposited primarily in subtidal environments. Progradation of Mauch Chunk alluvial plain sediments was concurrent with the Reynolds regression over much of West Virginia and Pennsylvania. The alluvial plain was apparently crossed by numerous streams that produced the fining-upward channel-fill sandstones, and during flood stages, much of the fine-grained overbank deposits.

PATTERNS OF SEDIMENTATION

One overriding theme is suggested by the study of the Upper Mississippian of the central portion of the Appalachian Basin: that numerous, small-scale, relative sea level oscillations are superimposed upon even larger trangressive and regressive sea level fluctuations (Brezinski, 1986). Inasmuch as biostratigraphic controls regarding the duration of the alternations is poor, the current report follows the proposal of Wright (1986) in assigning cycle order, based upon their relative recognition (i.e., thickness and lateral extent) in the rock record. Under this scheme, for example, 4th-order transgressive-regressive units are superimposed upon a 3rd-order unit. Insofar as the entire Meramecian-Chesterian section represents a regressive/progradational phase of the Kaskaskia Sequence of Sloss (1963) this represents the largest scale of transgressive-regressive unit recognized for this interval. Vail and others (1977) suggested that the Kaskaskia Sequence was a Devonian-Mississippian transgressive-regressive episode of the second-order [=synthem as used by Ramsbottom (1979), see Busch and Rollins (1984)]. Based upon the interpreted water depth of the component facies (Brezinski, 1984a) the Appalachian Meramecian-Chesterian section represents a single, more or less complete, transgressive-regressive unit (3rd-order unit) with stillstand occurring within the Wymps Gap. Within this scheme the Loyalhanna represents a shallow water transgressive phase, the Wymps Gap maximum transgression, and the Reynolds a regressional phase (Figure 14). Furthermore, each of the three major marine events (Loyalhanna, Wymps Gap, Reynolds) represents a single 4th-order transgressive-regressive unit (= mesothem of Ramsbottom, 1979). These 4th-order units inturn, are comprised of numerous discrete shallowing-upward episodes which are herein designated 5th-order units and are interpreted to be comparable to the cyclothems of Ramsbottom (1979). Fifth-order units are represented by individual shallowing-upward episodes contained within the Loyalhanna, Savage Dam clastic tongue, and Reynolds (see Figures 6, 9, and 12), and range in thickness from 1-8 m. No attempt was made here to identify smaller scales of transgressive-regressive units such as 6th-order or PAC level unit (Goodwin and Anderson (1983). Consequently, at least four scales of transgressive and regressive unit are present within the Meramecian-Chesterian strata of the Appalachian Basin. Fourth and 5th-order units are the most distinctive and easy to recognize inasmuch as an

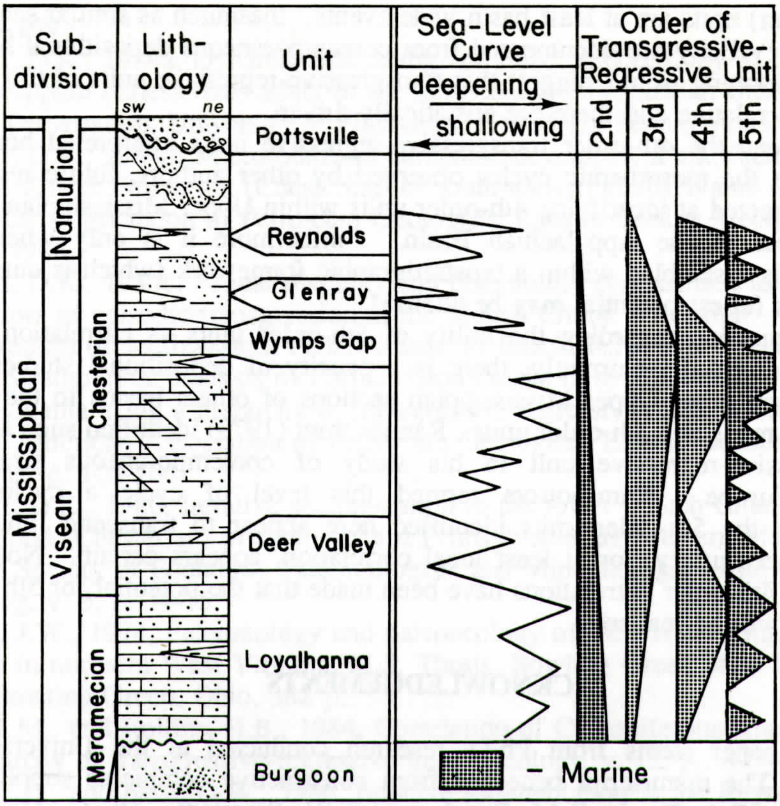

Figure 14. Interpreted relationships of lithologic units, sea level fluctuations, and orders of transgressive-regressive units within Meramecian-Chesterian strata of the north-central Appalachian Basin.

overall deepening and shallowing within them can be demonstrated based on lithofacies changes from marine to nonmarine.

Based upon intrinsic evidences an argument may be made that the apparent sea level fluctuations are autocyclic in nature and that they represent nothing more than manifestations of changing sediment input or subsidence. If this were the case one would expect that there would be a greater number of transgressive-regressive units to the southeast and east where subsidence and sediment influx were greater. Instead, the number of transgressive-regressive units increase to the west and southwest toward the marine seaway. This suggests that it is eustatic fluctuations that produced most of the facies changes identified here.

Several of the larger transgressive-regressive packages are almost certainly eustatic in nature. Ramsbottom (1979), Saunders and Ramsbottom (1986), Saunders and others (1979), Ettensohn (1980), and Maples and Walter (1987) have shown that certain eustatic events are recognizable within the Chesterian of North America and Visean and Namurian of Europe. Some authors (Saunders and others, 1979; Saunders and Ramsbottom, 1986; and Ross and Ross, 1985) have provided biostratigraphic evidence that certain mesothemic cycles may be correlatable worldwide. For the Appalachian Chesterian section, the mesothemic (i.e., 4th-order) units are at least basin-wide events. Inasmuch as similar scales of mesothemic cyclicity are documented from contemporaneous depositional basins, deductive reasoning would suggest that transgressive-regressive units of this scale should be correlative and therefore eustatically driven.

If indeed the 4th-order transgressive-regressive units interpreted here are equivalent to the mesothemic cycles observed by other authors, future research should be directed at identifying 4th-order units within Upper Mississippian strata in other areas of the Appalachian Basin. Furthermore it is only when this information is assembled within a biostratigraphic framework (which is currently poor) that its fullest potential may be attained.

The question regarding the utility of 5th-order units as correlation tools remains unanswered. Currently, there is a paucity of depositional studies that have examined other Upper Mississippian sections of others basins to the level necessary to recognize 5th-order units. Ramsbottom (1979) identified such a scale of transgressive-regressive unit in his study of contemporaneous strata of northwest Europe. Ramsbottom termed this level of cycle a cyclothem. Inasmuch as the 5th-order units identified here appear to transcend lithosome boundries there utility, for at least local correlation, appears certain. Not until unequivocal 4th-order correlations have been made that the potential for 5th-order correlations will be realized.

ACKNOWLEDGEMENTS

This paper stems from Ph.D. research conducted at the University of Pittsburgh. The manuscript benefited from constructive comments supplied by H.B. Rollins, C.A. Kertis, R.M. Busch, and T.W. Bjerstedt. Dr. G. Merrill is thanked for his views on nonWaltherian stratigraphy. Field work was supported by the Appalachian Basin Industrial Associates and the Maryland Geological Survey.

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CARBONATE DEPOSITION IN A SHALLOW MARINE GULF, THE MISSISSIPPIAN GREENBRIER LIMESTONE OF THE CENTRAL APPALACHIAN BASIN

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ABSTRACT

A basin-wide paleogeographic model for the Upper Mississippian Greenbrier Limestone and equivalents was constructed by mapping the distribution of correlative sediments across the north-central region of the Appalachian Basin. During late Meramecian and Chesterian time, the Greenbrier Limestone was deposited over a broad shallow shelf which extended into parts of Ohio, Kentucky, West Virginia, Pennsylvania, and Maryland. Depositional facies recognized include, 1) tidal-flat, 2) restricted-gulf, 3) open-gulf, 4) open-marine, 5) ooid-shoal, 6) flooded-shoal, and 7) coastal-sand-flat environments. The Greenbrier Limestone formed during a transgression of the sea into the central Appalachian Basin. Outcrops record this transgression as open-marine conditions replaced shallow, somewhat restricted, and nearshore to exposed environments throughout the basin.

INTRODUCTION

The Upper Mississippian Greenbrier Limestone records a major transgression of an epeiric sea into the central Appalachians. Paleomagnetic evidence indicates that the Appalachian Basin was located approximately 10° south of the equator (Edmunds and others, 1979), and the combination of warm climate and shallow seas provided ideal conditions for carbonate production.

Although the Greenbrier Limestone and its equivalents have been measured and described at numerous localities (Scatterday, 1963; Hoque, 1968; Leonard, 1968; Wray and Smosna, 1982; Brezinski, 1984; Ettensohn and others, 1984; Yeilding, 1984; Tissue, 1986, Sullivan and Textoris, 1988), a basin-wide depositional model is lacking. The present study examines eleven exposures of the Greenbrier Limestone from an extensive area within the central Appalachians, including northeastern Kentucky, eastern Ohio, southwestern Pennsylvania, northern West Virginia, and western Maryland (Figure 1). Many of the localities are active or inactive limestone quarries where the maximum thickness of section is exposed. Stratigraphic and petrographic studies provide the basis for an interpretation of depositional environments and regional trends in sedimentation. The purpose of this paper, therefore, is to provide a sedimentological-paleogeographical model for this stratigraphic unit.

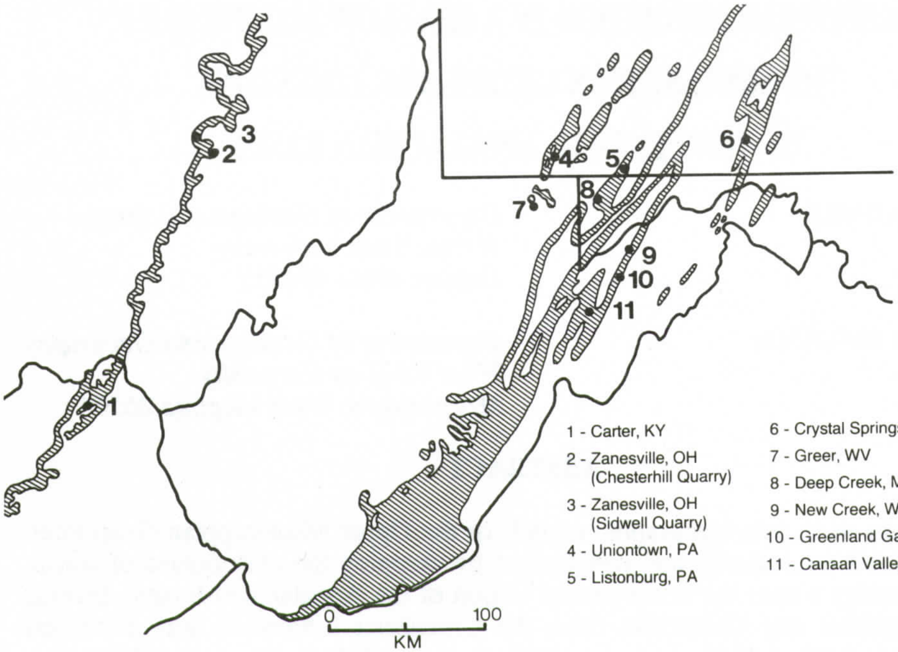


Figure 1. Outcrop pattern of Mississippian rocks in the study area. Localities are numbered.

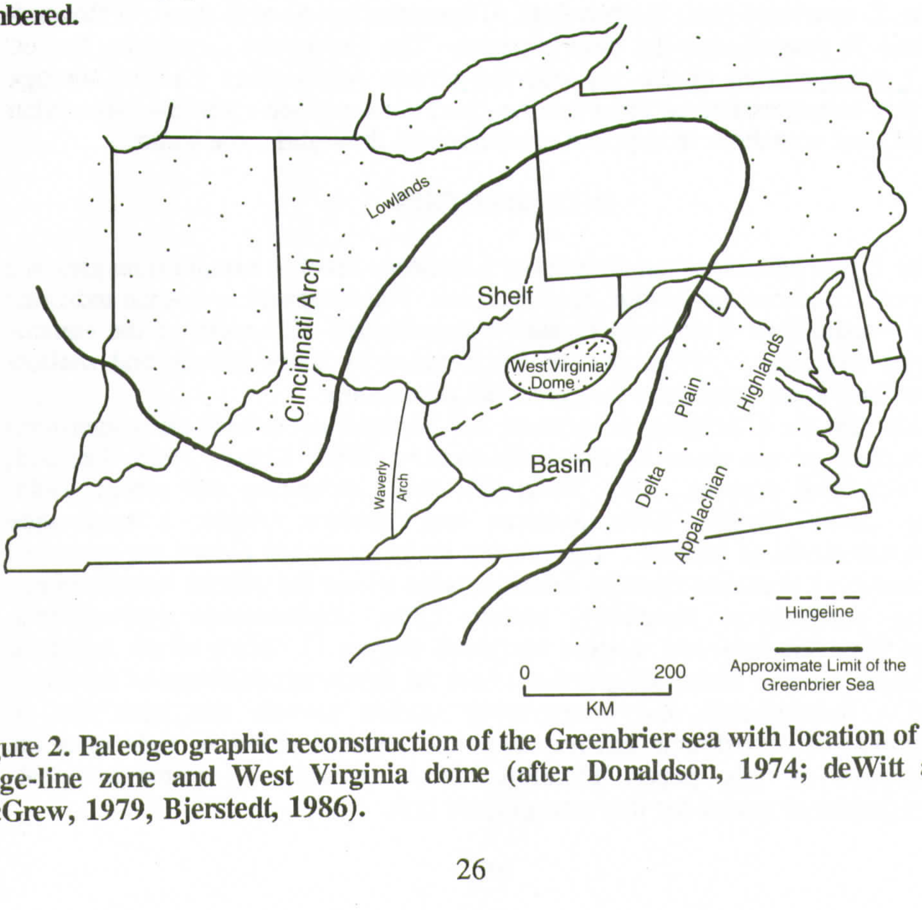


Figure 2. Paleogeographic reconstruction of the Greenbrier sea with location of the hinge-line zone and West Virginia dome (after Donaldson, 1974; deWitt and McGrew, 1979, Bjerstedt, 1986).

GEOLOGICAL SETTING

The depositional setting for the Greenbrier Limestone included a continually subsiding basin centered in southeastern West Virginia and adjacent Virginia, separated by a hinge zone from a broad, shallow shelf located to the north and northwest (Figure 2) (Arkle and others, 1979). The basin is a tectonic feature, consisting of a very thick sequence of shallow-water deposits. Carbonate deposition began in the basin, spreading gradually northward across the shelf. This study concentrates on Greenbrier sedimentation of the northern shelf where a variety of carbonate facies developed.

Most of the structural elements that influenced Mississippian sedimentation in the Appalachian Basin were relics of the Devonian or earlier (Craig and Varnes, 1979). The Appalachian Basin was bordered on the west by the Cincinnati arch, on the east by the Appalachian highlands, and on the north by exposed lowlands (deWitt and McGrew, 1979). Deltaic-coastal plain deposits periodically spread across the basin from the east (Hoque, 1968; Edmunds and others, 1979; Brezinski, 1984).

There is evidence that the Waverly Arch and the Kentucky River fault system of northeastern Kentucky may have been active intermittently during Greenbrier deposition, causing local variations in areal distribution and stratigraphic thickness and producing sedimentary features indicative of subaerial exposure (Dever, 1980). The pronounced subsidence of the southern basin in West Virginia and Virginia and the great thickness of sediment deposited (greater than 500 meters) may be indicative of minor tectonism in this area as well (Arkle and others, 1979). To the north and west, a much thinner package of sediments (only 30 to 100 meters) was deposited on the shelf. Between the two areas, sediments thin over a relatively short distance suggesting the presence of a hinge-line zone (Arkle, 1969; Donaldson, 1974). The hinge-line zone is generally placed along the 100-meter (300-foot) contour line of Flowers' (1956) isopach map of the Greenbrier Formation. An area of uplift, the West Virginia dome, developed along the hinge-line zone in north-central West Virginia. Yeilding and Dennison (1986) believed that this feature is an expression of the 38th Parallel lineament (Zartman and others, 1967), which might extend across West Virginia and connect with the Kentucky River fault system. Donaldson and Shumaker (1981) and Bjerstedt (1986), however, placed the 38th Parallel lineament further to the south.

REGIONAL STRATIGRAPHY

Upper Mississippian limestones are present throughout the central Appalachian Basin, and although they have not been correlated in detail, they have for many years been considered stratigraphically equivalent (Stevenson, 1903; Morse, 1910; Rittenhouse, 1949; Flowers, 1956; Uttley, 1974). A major problem, as in the case of many other units, is that equivalent strata have been assigned different names across state boundaries. Attempts at a basin-wide correlation have also been hampered by the lack of a distinctive macrofauna, the lithologic variability of the limestones, and the presence of unconformities around the basin edges. The present investigation provides a detailed depositional study of Upper Mississippian limestones of the central Appalachian Basin but relies on previously

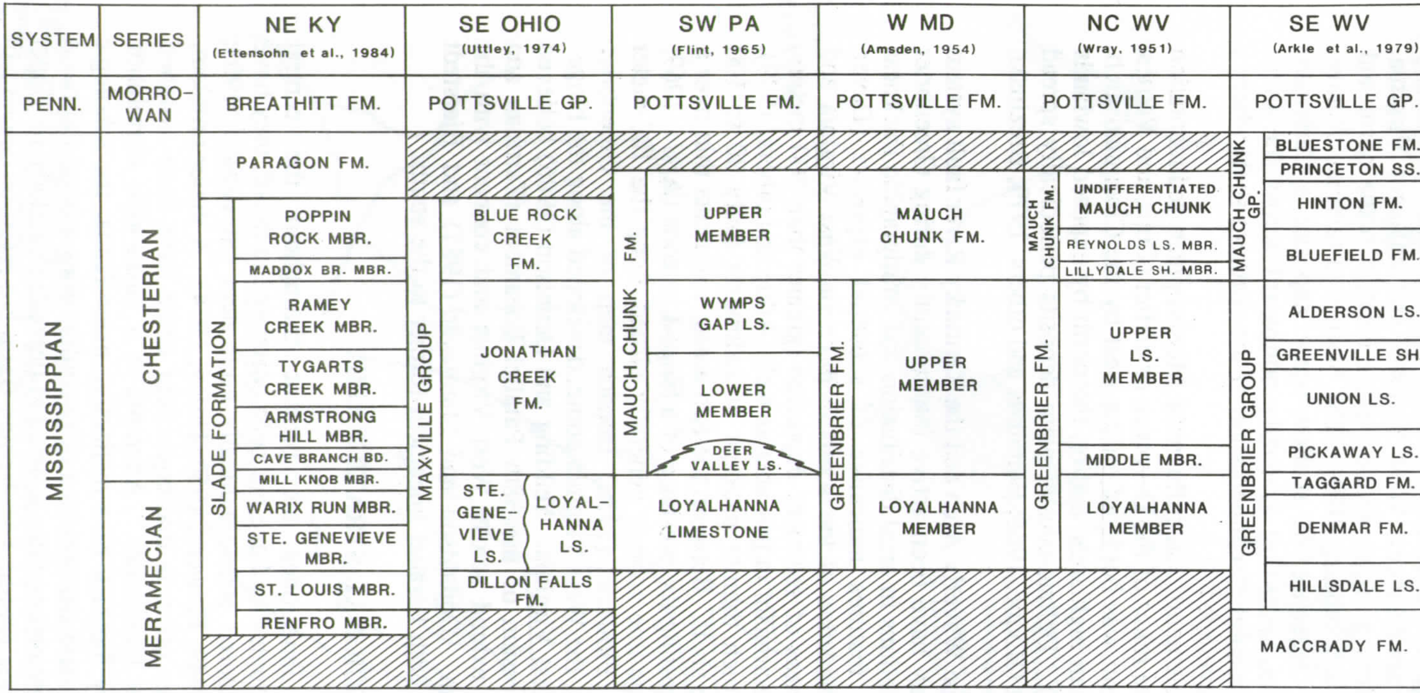


Figure 3. Upper Mississippian nomenclature and correlation for the central Appalachian Basin (after Wray, 1951; Amsden, 1954; Flint, 1965; Uttley, 1974; Arkle and others, 1979; Ettensohn and others, 1984; Carney, 1987).

published work for stratigraphic detail (Figure 3).

The Greenbrier Limestone is recognized in West Virginia, Maryland, Virginia, and in some areas of Pennsylvania. Equivalents include the Slade Formation (Newman Limestone) of Kentucky (Ettensohn and others, 1984), the Maxville Limestone of Ohio, and the Loyalhanna Limestone and the Deer Valley, Wymps Gap, and Trough Creek Members of the Mauch Chunk Formation in Pennsylvania. These units are generally considered middle to late Meramecian and early Chesterian in age (Horowitz and Rexroad, 1972).

FACIES ANALYSIS

The Greenbrier Limestone can be divided into the following seven distinct shallow-water depositional facies: tidal-flat, restricted-gulf, open-gulf, open-marine, ooid-shoal, flooded-shoal, and coastal-sand-flat environments. Figure 4 shows the juxaposition of facies of the Greenbrier Limestone. The coastal-sand-flat and oolitic facies are not present at every study locality, and are shown separately. Relative abundances of various constituents are depicted beneath each facies, emphasizing major differences among the facies.

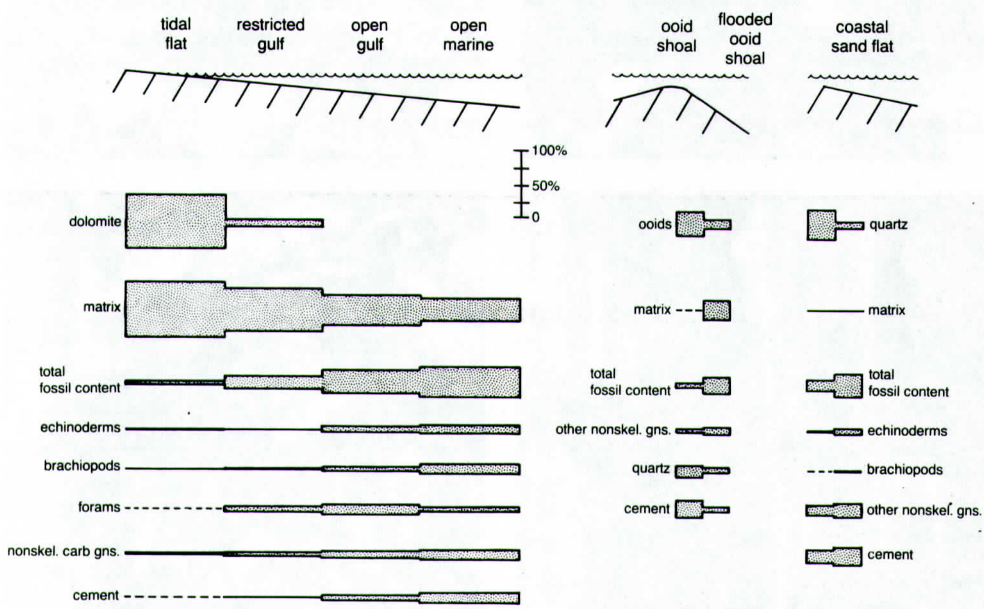
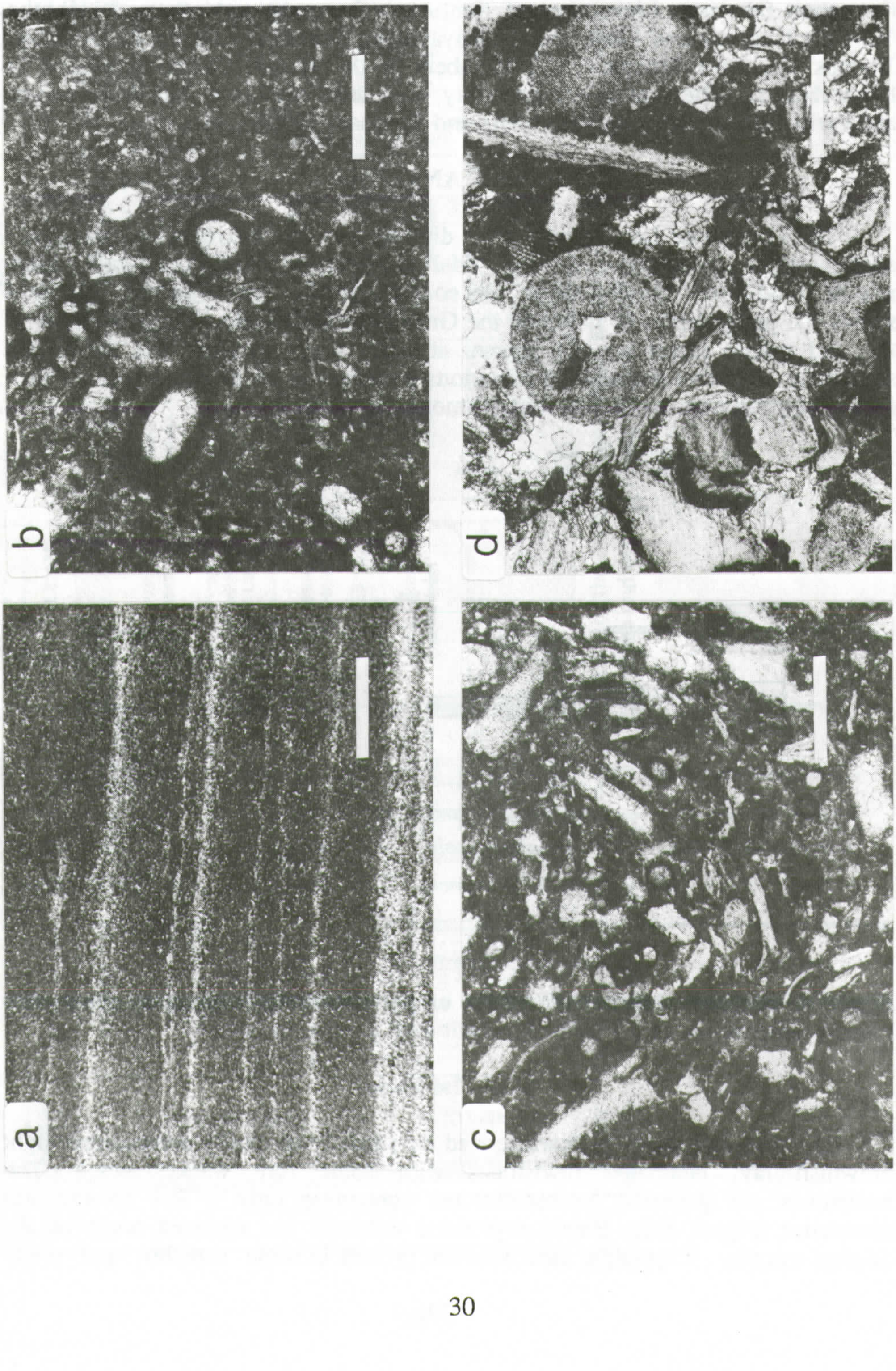


Figure 4. Diagram showing the facies of the Greenbrier Limestone along with relative proportions of the various constituents present in each.

Tidal-Flat Facies

The tidal-flat facies is characterized by partially to totally dolomitized, light brownish-gray, laminated mudstones with some rare wackestones. The mudstones are generally unfossiliferous, containing only a few forams and ostracodes (Figure 5a). Finely crystalline dolomite has replaced much of the original micrite. Cryptalgal structures are present in some samples, and mud-


a
b
c
d

cracks are also recognized. Rounded, elongate intraclasts, where present, are concentrated in thin layers. The wackestones contain a small percentage of peloids and skeletal fragments, including brachiopods and pelmatozoans.

Deposition on a carbonate tidal flat is suggested by the lithology, sedimentary structures, and the scarcity of fossils. Most lithologies suggest supratidal deposition, with a few subtidal wackestones also represented. Carbonate muds, partially to completely replaced by microcrystalline dolomite, are characteristic of tidal-flat environments (Asquith, 1979). Muds washed in from offshore by tidal currents and storms accumulate on flats because energy levels are not high enough to wash them away (James, 1984). The mechanism of dolomitization for these limestones was not considered for this study; however, dolomite is forming today on arid supratidal flats of the Persian Gulf and as crusts on supratidal flats of the Florida Keys and the Bahamas (Bathurst, 1975).

Many sedimentary structures characteristic of tidal-flat deposition are present in this facies. Lamination is produced by intermittent deposition above high tide where flooding is infrequent and breaks in sedimentation occur (Shinn, 1983). Algal mats are characteristic of upper intertidal to supratidal environments where they form as a result of alternating algal growth and sediment influx (Logan and others, 1964; Shinn, 1983). Mudcracks indicate subaerial exposure and desiccation of the sediments. Thin beds of intraclasts represent erosion and re-deposition of mudcrack fragments and chips of algal mats (Folk, 1959; Matter, 1967).

Only a few types of shelly organisms can tolerate the high physiological stress of a tidal flat. Periodic exposure and variable temperature and salinity restricted the community to a few tolerant forams and ostracodes. Brachiopods and pelmatozoans may have been washed into this environment from the adjacent subtidal, but evidence is lacking.

Restricted-Gulf Facies

Gray, thin-bedded to massive limestones with shaly partings make up the restricted-gulf facies of the Greenbrier Limestone. Fossils are very rare on outcrop. In thin section, this facies is represented by sparsely fossiliferous mudstones and wackestones (Figure 5b). Fossils are dominantly forams, ostracodes, gastropods, and encrusting calcareous algae (*Girvanella*). Sponge spicules are rare. Fossils are whole and unabraded, and the muddy sediments are

Figure 5. a) Photomicrograph of thin section of dolomitized, laminated mudstone of the tidal-flat facies from the lower Jonathan Creek Formation at Zanesville, Ohio. Plane-polarized light. Scale bar, 2.5mm. b) Photomicrograph of thin section of foram-ostracode mudstone of the restricted-gulf facies from the Tygarts Creek Member of the Slade Formation at Carter, Kentucky. Plane polarized light. Scale bar, 0.25mm. c) Photomicrograph of thin section of brachiopod-foram packstone of the open-gulf facies from the upper limestone member of the Greenbrier Formation at Greer, West Virginia. Plane polarized light. Scale bar, 0.5mm. d) Photomicrograph of thin section of crinoid packstone of the open-marine facies from the upper limestone member of the Greenbrier Formation at Greenland Gap, West Virginia. Plane-polarized light. Scale bar, 0.5mm.

pelleted and extensively burrowed. Noncarbonate constituents include minor quartz silt and pyrite.

This facies represents deposition in a shallow, restricted environment. A low-diversity fauna of forams, ostracodes, and gastropods inhabited the restricted gulf along with inferred soft-bodied organisms that were responsible for burrowing. The impoverished fauna suggests stress caused by poor circulation. Restriction was not produced by a barrier, but rather resulted from the large body of shallow water over which waves and currents traversed (Shaw, 1964). Ocean currents and waves had lost so much energy by the time they reached the restricted gulf that water movement was minimal. The restricted currents could not provide needed nutrients or sufficient oxygen levels for diverse animal life. Conditions were not anoxic, but neither were they optimal. Although circulation was restricted, the sediments were capable of supporting infaunal organisms as indicated by the presence of numerous horizontal burrows.

The environment was shallow, but always subtidal. No evidence of subaerial exposure was found in any of the samples. Micritic envelopes and the presence of algae indicate that the environment was within the photic zone (Riding, 1975). Low energy is indicated by the abundance of mud, preservation of soft fecal pellets, and lack of abrasion of fossil fragments (Dunham, 1962; Bathurst, 1975).

Open-Gulf Facies

Limestones of this facies are not easily distinguishable from those of the restricted gulf, except that fossils, especially brachiopods, are more common on outcrop. Gray, thin-bedded to massive, fossiliferous wackestones and packstones characterize the open-gulf facies of the Greenbrier Formation (Figure 5c). Forams achieve greatest numbers in this facies and average around 14 percent by volume of most samples. Other skeletal grains include impunctate, punctate, and pseudopunctate brachiopod shells, pelmatozoan columnals, and mollusc fragments. Fenestrate bryozoans and ostracodes are common constituents, encrusting algae including *Girvanella* are minor, and trilobites, sponge spicules, and fish fragments are rare. Skeletal grains are whole or broken with little sign of abrasion.

Silt- to fine-sand size, spherical pellets are minor to common, and are probably fecal in origin. Burrows are preserved; most are oriented horizontally. A few intraclasts and algally coated grains are also present. Noncarbonate constituents include detrital quartz and pyrite. Argillaceous material, concentrated in thin wispy laminae, is common in samples from the northeastern part of the study area.

This facies represents sedimentation in a shallow, open-gulf environment where muddy skeletal sands were deposited. No restriction is evident, and normal conditions of circulation and salinity are indicated by the moderately diverse fauna. Both epifaunal and infaunal organisms are present, and a fairly high percentage of suspension feeders such as crinoids and fenestrate bryozoans is evidence of an adequate suspended food supply. However, the moderate fossil diversity and abundance suggests that conditions may not have been optimal, and stenohaline forms are less prevalent than in the open-marine facies described in the following section. Abundant forams imply an environment suitable for these benthic organisms to proliferate.

The accumulation of significant lime mud indicates weak currents, baffling by noncalcareous organisms, or very rapid mud production. Thick micritic envelopes and micritized grains are evidence that the environment was within the photic zone and that the sedimentation rate was low enough that grains lying on the sea floor could be bored by algae or fungi (Bathurst, 1975). Low to moderate energy is also indicated by the abundance of whole, unabraded fossils. Any fragmentation of fossils was probably the result of bioerosion (Payton, 1966). The bottom was below normal wave base, but may have been occasionally disrupted by storms that ripped up and re-deposited semi-lithified sediments and skeletal fragments, forming intraclasts and thin beds of fossil hash.

Open-Marine Facies

Lithologies of the open-marine facies consist of wackestones and packstones with abundant skeletal fragments including pelmatozoan columnals, echinoid spines, impunctate, punctate, and pseudopunctate brachiopod shells, brachiopod spines, fenestrate and encrusting bryozoan colonies, tubular and endothyrid foram tests, gastropod and pelecypod shells, calcareous algae (*Girvanella* and others), ostracode valves, and rare trilobite and fish fragments (Figure 5d). On outcrop, limestones of this facies are similar in appearance to those of the open-gulf facies. In thin section, however, all skeletal grains except forams are more abundant. Skeletal grains commonly have micritic envelopes, are whole or broken, and show little evidence of abrasion. A few well-developed oncolites and grains with thin algal coatings were also identified.

Pellets, found in many samples, are fine- to medium-sand size and are probably fecal in origin. Micritized skeletal grains (peloids) are more common than pellets, however. The wackestones and packstones are commonly burrowed or bioturbated, and borings are occasionally present in skeletal grains. The micritic matrix is sometimes argillaceous especially in samples from the northeast outcrops. Intragranular and intergranular cements occur in most samples.

The depositional setting suggested is an open-marine environment with normal circulation and salinity. This environment supported a highly diverse fauna characterized by abundant pelmatozoans and brachiopods. The overall abundance of suspension-feeding organisms such as crinoids, fenestrate bryozoans, and brachiopods suggests that currents brought in a more than adequate supply of food, and the high numbers of stenohaline organisms implies constant, normal salinities. The warm, clear, shallow waters of the open-marine environment provided optimum living conditions for many organisms including infaunal and epifaunal, deposit and suspension feeders.

The presence of skeletal algae, oncolites, and micritized grains are evidence of a shallow environment within the photic zone. Moderate- to low-energy conditions are suggested by the lack of abrasion of skeletal fragments, the high mud content, and the preservation of pellets. The open-marine environment may represent a somewhat deeper environment than the open-gulf facies, and slightly deeper waters may have offered better circulation and a more stable environment in terms of temperature and salinity for organisms living there (Tasch, 1973).

A few samples from this facies contain significant intergranular cement.

These moderately-washed packstones are evidence that energy conditions on the sea floor were at times sufficient to wash away lime mud matrix or that mud productivity was occasionally low.

Ooid-Shoal Facies

Rocks of this facies are light gray to reddish-gray, oolitic limestones with bidirectional, planar cross-bedding. Cross-bed sets vary in thickness from several centimeters to 1.0 meter. The limestones appear nearly unfossiliferous on outcrop.

In thin section, the ooid-shoal facies consists of ooid grainstone cemented by fine to medium crystalline, granular or drusy calcite cement (Figure 6a). Ooids are abundant, averaging 60 percent of the total grain content. Ooids are typically medium-sand size and are found in all stages of micritization. Many of the ooids are superficial, with only one or two oolitic coatings. A variety of grains serve as nuclei, including peloids, intraclasts, and skeletal fragments, especially pelmatozoan columnals and foram tests. The ooid grainstones have an "overpacked" appearance, grains are often interpenetrating or appear squeezed together. Broken and spalled ooids have also been identified.

Uncoated skeletal grains average seven percent of the rock by volume and include pelmatozoan fragments, brachiopod shells, ostracode valves, foram tests, and bryozoan colonies. Most are broken and show signs of abrasion. Peloids are common and appear to be micritized ooids or skeletal grains. Intraclasts are micritic and have inclusions of quartz silt and small fossils.

A few, thin, skeletal wackestones are found interbedded with the oolitic grainstones. The wackestones consist of brachiopods, forams, pelmatozoan columnals, bryozoans, and ostracodes in a muddy matrix, and resemble samples from the open-gulf facies discussed previously.

This oolitic facies represents deposition on and around a topographic high. The near absence of micrite, the rounding of allochems, oolitic coatings, good sorting, and cross-bedding all indicate sedimentation on a well-agitated bottom in shallow water. The abundant micritized ooids and thick micritic envelopes suggest that grains rested on the sea floor as a relict ooid deposit for some time before burial, probably due to a relatively slow sedimentation rate (Purdy, 1963).

Conditions for ooid production must have been less than perfect, considering the rather low percentage of ooids with thick lamellae. Well-developed ooids require supersaturated water, agitation, and available nuclei (Newell and others, 1960; Donahue, 1969; Bathurst, 1975). One or more of these conditions may not

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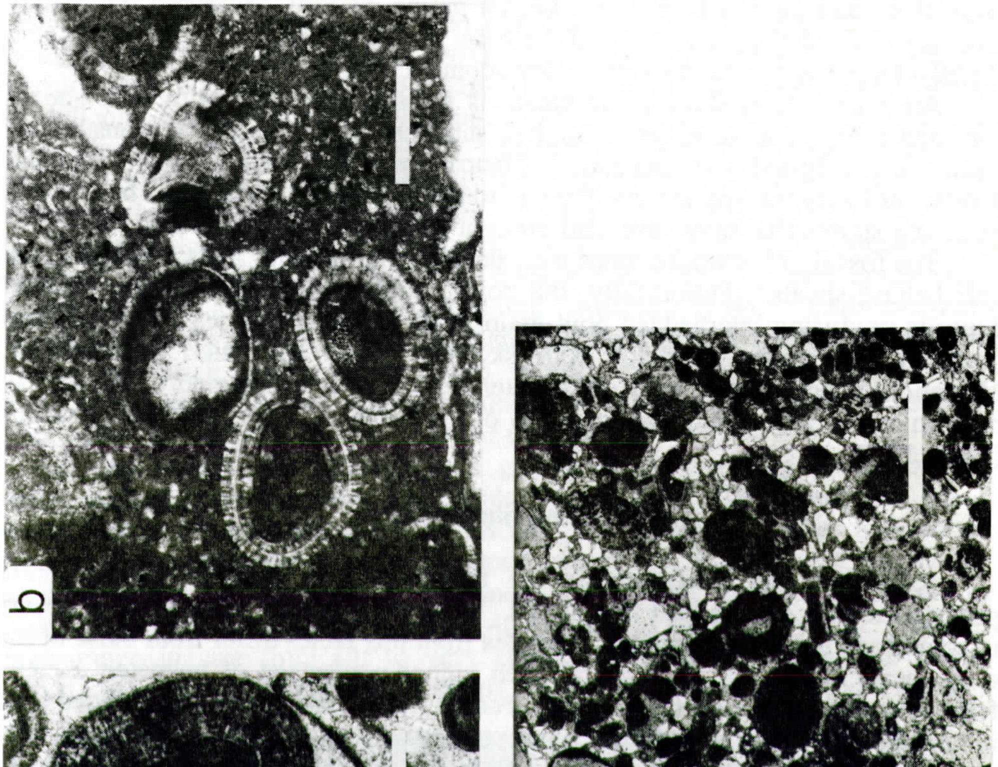
Figure 6. a) Photomicrograph of thin section of well-developed oolitic grainstone typical of the ooid-shoal facies from the Denmar Formation at Canaan Valley, West Virginia. Plane polarized light. Scale bar, 0.25mm. b) Photomicrograph of thin section of oolitic packstone of the flooded-shoal facies from the Alderson Limestone at Canaan Valley, West Virginia. Plane polarized light. Scale bar, 0.25mm. c) Photomicrograph of thin section of sandy grainstone of the coastal-sand-flat facies from the Loyalhanna Member of the Greenbrier Formation Note broken and abraded ooids and abundant peloids. Plane polarized light. Scale bar, 0.5mm.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have been ideal in this Greenbrier environment. The presence of thinly-coated (superficial) ooids suggests that currents were not always energetic enough for ooid production. Current energy was sufficiently strong, however, to winnow away fines and to round and sort skeletal grains. Poorly-developed ooids may have also formed along the flanks of the shoal or in near-shoal environments where slightly deeper water inhibited their development (Harris, 1979).

An extremely shallow environment is usually associated with ooid shoals, and high energy conditions and a mobile substrate were probably responsible for the low diversity and low abundance of fauna (Raup and Stanley, 1978). Skeletal debris was likely transported into the environment from off-shoal areas by currents or during storms that may have also brought in the micritic intraclasts.

The fossiliferous wackestones were deposited in subtidal areas, perhaps in the gulf behind shoals. Periodically, the oolitic shoals migrated over the subtidal deposits producing interbedded ooid grainstones and wackestones. The gulf was probably the source area for both skeletal grains and micritic intraclasts. Migration of ooid shoals over quiet-water sediments is a common occurrence in modern carbonate-forming environments of the Bahamas, especially during storms (Hine, 1977).

Flooded-Shoal Facies

Rocks of this facies consist of thin-bedded to massive, gray, oolitic packstones with interbedded thin shales. Low-angle planar cross-bedding occurs in some beds but is not common. Samples from this facies differ from those of the ooid shoals in that they contain a much higher percentage of uncoated skeletal fragments and more mud (Figure 6b). Fossils appear somewhat less abraded than in the ooid-shoal facies. Brachiopods, pelmatozoan columnals, bryozoans, and endothyrid forams are the most common fossils, but tubular forams, gastropods, and pelecypods are also present. Ooids are not as abundant (averaging 12% of the total volume) or as well developed in the flooded shoals. Many are superficial oolitic coatings around skeletal nuclei. Grapestones are also recognized in this facies.

Peloids from this facies have irregular shapes, suggesting that they may be micritized skeletal grains. Micritic intraclasts are common constituents as is fine- to medium-sand-size detrital quartz.

This facies formed as a result of flooding of the ooid shoals, and in the deeper water, conditions were far from ideal for ooid production. The presence of grapestones is evidence for seafloor stabilization, low sedimentation rate, and supersaturated water (Purdy, 1963; Bathurst, 1975). Superficial ooids probably reflect sediment stability as well. Water depth was somewhat greater than over the active ooid shoals, and the more stable substrate allowed colonization by a variety of organisms. Unbroken, unabraded skeletal grains indicate that organisms were living within the flooded shoal. Hydrodynamic energy was not strong or consistent enough to prevent the accumulation of mud between grains. Intraclasts and some mud-free samples may indicate periodic higher-energy conditions, however.

Coastal-Sand-Flat Facies

On outcrop, the coastal-sand-flat facies consists of brownish-gray, greenish-gray, or reddish-gray, sparsely fossiliferous, sandy grainstone and calcareous quartz sandstone. A regional color zonation has been recognized within rocks of this facies (Amsden, 1954; Adams, 1964). In most areas the sandy limestones are brownish-gray; however, on the northeastern side of the basin, a red facies is seen. The red color may be produced by hematite that occurs as discrete grains, matrix, and coatings on quartz (Adams, 1970). At some outcrops, the basal grainstones have been dolomitized. The percentage of quartz is highly variable from outcrop to outcrop and even within the same bed in a single outcrop.

Rocks of this facies are magnificently cross-bedded (Figure 7). Most of the cross-beds are less than 1.5 meters in thickness and have a form gradational between tabular and trough cross-bedding (Adams, 1964). Carbonate-rich laminae commonly contain fine- to medium-sand sized grains, whereas quartz-rich laminae are often coarser-grained and project out from the outcrop upon weathering. Wavy-bedded, planar-bedded, and massive grainstone units also occur within the section, but are of minor importance.

In thin section, the lithology is a grainstone with varying proportions of quartz, skeletal grains, peloids, and ooids (Figure 6c). The grainstones grade locally into carbonate-cemented sandstones or siltstones. The terrigenous component is dominantly quartz with minor amounts of feldspar, rock fragments, and heavy minerals. The total quartz content varies from less than 20 percent to nearly 75 percent, but averages around 40 percent of the total volume. Quartz grains range in size from silt to very coarse-grained sand. Carbonate grains include, in order of abundance, peloids, skeletal fragments, ooids, and micritic

Figure 7. Cross-bedding in the Loyalhanna Limestone at Greer, West Virginia. Meter stick provides scale.

intraclasts. Peloids are fine- to medium-sand size and appear, in many cases, to be micritized representatives of other carbonate grains, especially ooids and endothyrid forams. Ooids are variable in abundance but usually make up only a few percent of the sample. Some are very well developed; others are superficial with only one oolitic coating. Skeletal fragments include pelmatozoan columnals, forams (mainly endothyrids), bryozoan colonies, brachiopod shells, and rare ostracode valves and gastropod shells. Fossil fragments are commonly rounded and partially to totally micritized.

Previous interpretations of rocks from this facies have included (1) eolian deposits (Butts, 1924; Hickok and Moyer, 1940) because of the large-scale cross-bedding, lack of fossils on outcrop, and the presence of frosted quartz grains, or (2) beach complex (Rittenhouse, 1949; Flowers, 1956; Flint, 1965) based on the tabular form of the sand bodies, presence of marine fossils, and the lack of frosted quartz in most exposures. Adams (1964) showed that the rocks contain an abnormal amount of fines for an eolian or beach deposit and supported a shallow-water shelf as the most likely depositional environment. A marine interpretation is also suggested by the occurrence of marine fossils, the presence of equivalent purer limestones to the south, and the marine nature of overlying units (Adams, 1970).

Outcrops examined in the present study support the interpretation of a subtidal coastal sand flat. The sediment was deposited as low-relief sand waves less than 1.5 meters in height. The internal structure of avalanche-style cross-bedding indicates moderate-energy bottom currents (Imbrie and Buchanan, 1965). In places, the sand bodies built up into very shallow water of the upper flow regime, and the cross-bedded units were capped by horizontal beds or sheet deposits.

Evidence suggests that the small ooid population was transported onto the sand flat and mixed with the terrigenous clastic component. Broken and re-rounded ooids are common, and nuclei are exclusively peloids and fossil fragments. If the ooids were forming on the sand shoal itself, the abundant quartz grains present would surely have served as nuclei. Furthermore, the low ooid content of most samples indicates that the sand shoal was not an ooid-forming environment. Ooid shoals have been identified in equivalent rocks of central West Virginia (Youse, 1964; Wray and Smosna, 1982; this study), and these offshore shoals were probably the source for the coastal-sand-flat ooids.

Skeletal grains were reworked as evidenced by extensive abrasion. The sand shoal and adjacent areas were highly stressed environments because of moderate energy conditions, mobile substrate, and variable temperature and salinity resulting from the very shallow water conditions (Purdy, 1963; Halley and others, 1983). Thus, most organisms probably lived elsewhere and were transported in by currents. A few organisms may have inhabited the troughs between sand waves, however, where the substrate was somewhat more stable.

All types of carbonate grains show evidence of micritization. Micritization by boring algae or fungi in the well-lit waters occurred during times of decreased shoal migration or occasional burial, in troughs, or in environments adjacent to the active sand waves (Bathurst, 1975).

Lateral variations in the coastal-sand-flat facies include a higher fossil and peloid content and a significantly lower quartz component in samples from southwestern exposures because of increasing water depth and distance from the source of quartz sand (Figure 4).

HISTORY OF FACIES DEVELOPMENT

By mapping the distribution of correlative sediments across the north-central region of the Appalachian Basin, a paleogeographic model has been generated for the Greenbrier Limestone and equivalents. During late Meramecian and Chesterian time, the Greenbrier Limestone was deposited over a broad shallow shelf which extended into parts of Ohio, Kentucky, West Virginia, Pennsylvania, and Maryland. The stratigraphic distribution of facies reflects the overall transgression of the Greenbrier sea into the central Appalachians. Limestone deposition occurred over an erosional surface produced during a period of regression earlier in the Meramecian. This erosion surface on underlying deltaic sediments (deWitt and McGrew, 1979) had a significant effect on carbonate deposition; limestone units in Ohio were deposited in topographic lows, and ooid shoals formed across highs and along shorelines of partially emergent hills in West Virginia (Youse, 1964; Uttley, 1974). Although the transgression was frequently punctuated by clastic influxes that complicate the picture, especially in the east, the overall rise of sea level occurred in three stages.

Stage 1

The Greenbrier sea was at first confined to the southern basin or depocenter, and initial transgression across the northern shelf resulted in deposition of the coastal-sand-flat facies. This facies is represented by the Loyalhanna Limestone in West Virginia, Maryland, and Pennsylvania and the Warix Run Limestone in Kentucky (Figure 3). According to Berg and others (1986), the Trough Creek Member of the Mauch Chunk in Pennsylvania is very similar lithologically to the Loyalhanna and may be an equivalent as well. The sand flat extended along the northern and western shorelines of the Greenbrier gulf (Figure 8). The gulf was open to the sea on the south and southwest, and shoaled to the north where there was an influx of terrigenous clastic material. Offshore facies in the south are assumed where equivalents of the Loyalhanna-Trough Creek-Warix Run were not investigated. Iron-bearing minerals were washed into the sand-flat facies from the adjacent coastal plain, producing the eastern red facies (Adams, 1970).

A general north-to-south decrease not only in grain size but also in abundance of detrital quartz suggests a northern source for the terrigenous component (Rittenhouse, 1949; Flowers, 1956; Flint, 1965; Adams, 1964). DeWitt and McGrew (1979) suggested uplift and erosion of a portion of the Canadian Shield area in eastern Canada as the source for part of the terrigenous material. Additional source areas may have been present to the east, and the Cincinnati arch to the west may also have made minor contributions (Adams, 1970). Another likely source is the underlying quartz-rich Price and Burgoon Formations over which the sand flat transgressed (Rittenhouse, 1949).

A study of cross-bedding indicates that the sand waves migrated to the northeast under the influence of longshore currents (Adams, 1970). The normal cross-bedding direction was disrupted occasionally by reversing tidal currents and

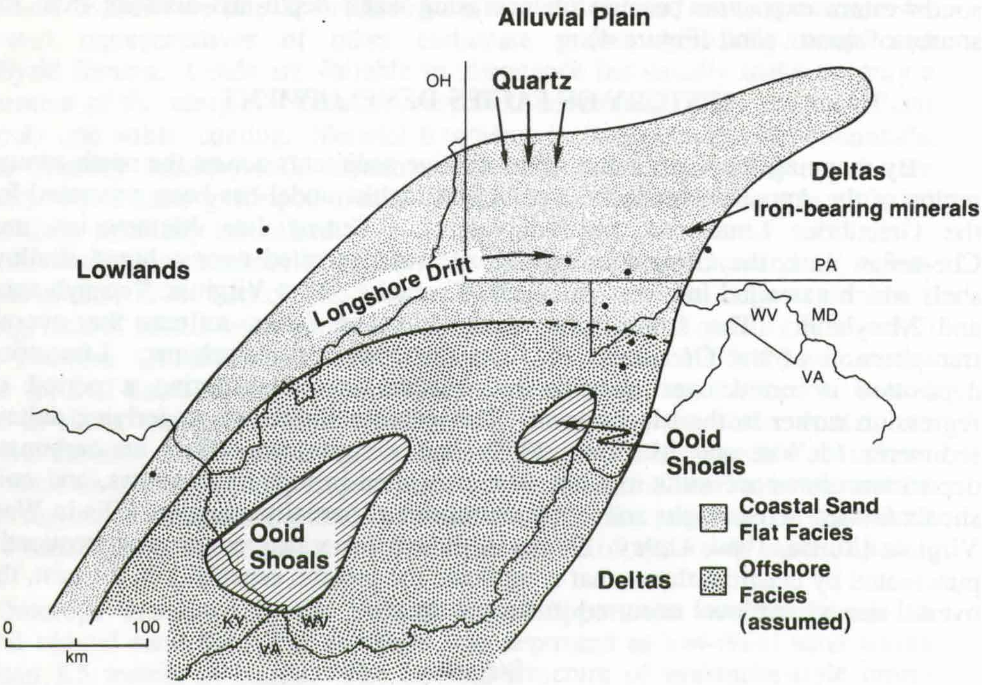

Figure 8. Paleogeography of the coastal sand flat, Stage 1. Direction of longshore drift after Adams (1970).

storms (Hoque, 1968; Adams, 1970). A gentle north-to-south regional paleoslope is indicated by decreasing tourmaline to zircon ratios to the southwest, the decrease in clastic grain size in the same direction, and an increase in carbonate material to the south (Hoque, 1968; Adams, 1970). Hence, currents responsible for migrating sand waves flowed perpendicular to paleoslope and parallel to the basin margin.

Simultaneous with the transgression of this coastal sand flat, an oolite facies of the Denmar Formation (Figure 3) developed around the West Virginia dome in the east-central part of the state. Yeilding (1984) recognized beds of micrite and dolomite characteristic of upper intertidal and supratidal environments over the uplift itself. Around the flanks of the uplift, cross-bedded oolitic grainstones formed on ooid shoals. Fossiliferous wackestones were deposited in subtidal areas away from the uplift. Periodically, ooid shoals migrated over these subtidal deposits, forming interbedded deposits. Ooid shoals were also located to the southwest in several counties of West Virginia, including Kanawha and Clay (Youse, 1964; Overbey, 1967).

To the northeast in Pennsylvania, sandy limestones interfingered with red deltaic deposits present along the eastern margin. Following deposition of the sandy Loyalhanna, fossiliferous packstones and coated grainstones of the Deer Valley Limestone (Figure 3) were produced in a small area of Pennsylvania (Brezinski, 1984).

After deposition of the sand flat, a pulse of terrigenous clastic sedimentation occurred over the northeastern part of the shelf, forming the middle clastic units of the Greenbrier Group (Taggard and unnamed member in West Virginia, lower member of Mauch Chunk in Pennsylvania; Figure 3) and temporarily shutting down carbonate deposition. These red and green siltstones, shales, and sandstones are relatively thin (averaging ten meters) in West Virginia, but thicken significantly to over 80 meters in southwestern Pennsylvania. These units have been interpreted as prograding alluvial-coastal plain deposits formed where sediment supply was greater than the rise of sea level (Hoque, 1968; Edmunds and others, 1979). At the same time, carbonate and terrigenous tidal flats developed to the south and southwest (Mill Knob Member and Cave Branch Bed of the Slade Formation, Kentucky). Rocks deposited during this time in Ohio are not preserved.

Stage 2

When terrigenous deposition ceased, carbonate sedimentation resumed on the shelf. At this time, the Greenbrier gulf was a few hundred kilometers wide and was surrounded by lowlands to the west and north (Figure 9). Deltaic sediments shed from nearby highlands periodically diluted the easternmost facies throughout deposition of the remainder of the Greenbrier Limestone, but clastics were never as abundant as in the coastal-sand-flat facies of Stage 1.

Several environments characterize deposition in the shallow gulf. Muddy skeletal sand was deposited in the central part where normal-marine circulation and salinities of the open-gulf facies developed. A moderately diverse fauna of brachiopods, crinoids, bryozoans, and abundant forams colonized the muddy bottom. Parts of the Tygart Creek and Ramey Creek Members of the Slade For-

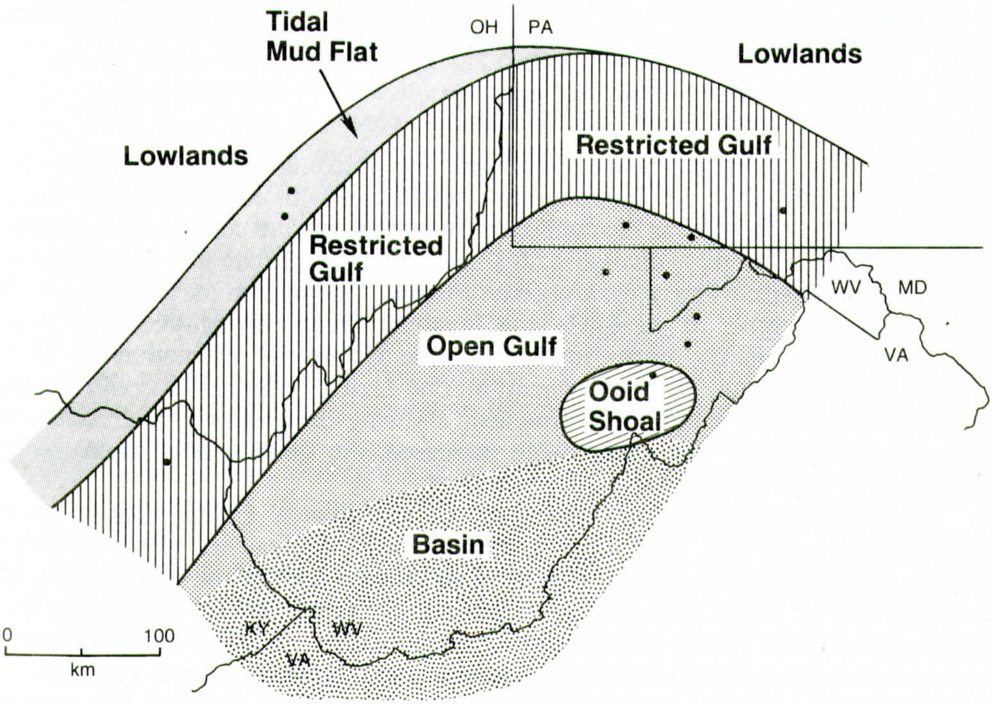

Figure 9. Paleogeography of the open gulf and associated environments, Stage 2.

mation, the Jonathan Creek Formation, the upper limestone member of the Greenbrier Formation, and the Wymps Gap Limestone (Figure 3) can be characterized as open-gulf facies.

From the central open area to the gulf margins, water depth decreased, circulation became more restricted, and salinities and temperatures may have been more variable. A restricted-gulf facies developed shoreward of the open gulf with sediments consisting of pelletal mud and scattered skeletal grains. Only a few organisms including forams, ostracodes, and gastropods could tolerate this restricted environment resulting from the vast expanse of shallow water over which waves and currents had to travel. This facies can be recognized in the central part of the Jonathan Creek Formation, the Tygarts Creek Member of the Slade Formation, and in lower part of the Wymps Gap Limestone.

A tidal-mud-flat complex was present shoreward of the restricted-gulf and may have surrounded the embayment on all three sides. Here, partially to totally dolomitized mud containing cryptalgal structures was deposited. These sediments were often subaerially exposed making conditions on the tidal flat unsuitable for many organisms. The Armstrong Hill Member of the Slade Formation and the lower part of the Jonathan Creek Formation (Figure 3) contain the tidal-flat facies. An apparent erosional surface is located at the top of this tidal-flat facies in the Jonathan Creek Formation in Ohio. Depressions of up to 0.5 meter occur in the upper surface; however, most of the surface is only slightly uneven.

Ooid shoals were again present on the eastern side of the gulf near the location of the West Virginia dome, now reduced to a submarine high, separating the gulf from the continuously subsiding basin to the south (Yeilding and Dennison, 1986). A significant influx of clastic material occurred during formation of these shoals, producing the sandy Pickaway and Union Limestones (Figure 3).

Stage 3

Eventually, as transgression continued, the epicontinental sea flooded the gulf, replacing all of the previous shallow-water facies with an open-marine facies (Figure 10). This facies was characterized by normal-marine conditions favorable for support of a highly diverse fauna including pelmatozoans, brachiopods, bryozoans, molluscs, ostracodes, and some forams. The uppermost sections of the Ramey Creek Member of the Slade, the Jonathan Creek Formation, the Wymps Gap Limestone, and the upper member of the Greenbrier Formation in West Virginia and Maryland, all contain open-marine facies. The eastern ooid shoals were flooded but not completely drowned, allowing deposition of the Alderson Limestone (Figure 3). As water depth increased, the flooded ooid shoals were colonized by a variety of benthic organisms.

Marine and fluvio-deltaic sediments of the Mauch Chunk and Paragon Formations overlie the Greenbrier Limestone and equivalents (Hoque, 1968; Presley, 1979; Ettensohn, 1980). Uplift of the source land to the east resulted in progradation of these terrigenous sediments over the shelf, displacing the Greenbrier sea and finally ending carbonate deposition. A short-lived trangressive event occurred during Mauch Chunk deposition, however. Once again open-marine conditions were present throughout the basin, and the thin but areally extensive Reynolds Limestone Member was deposited.

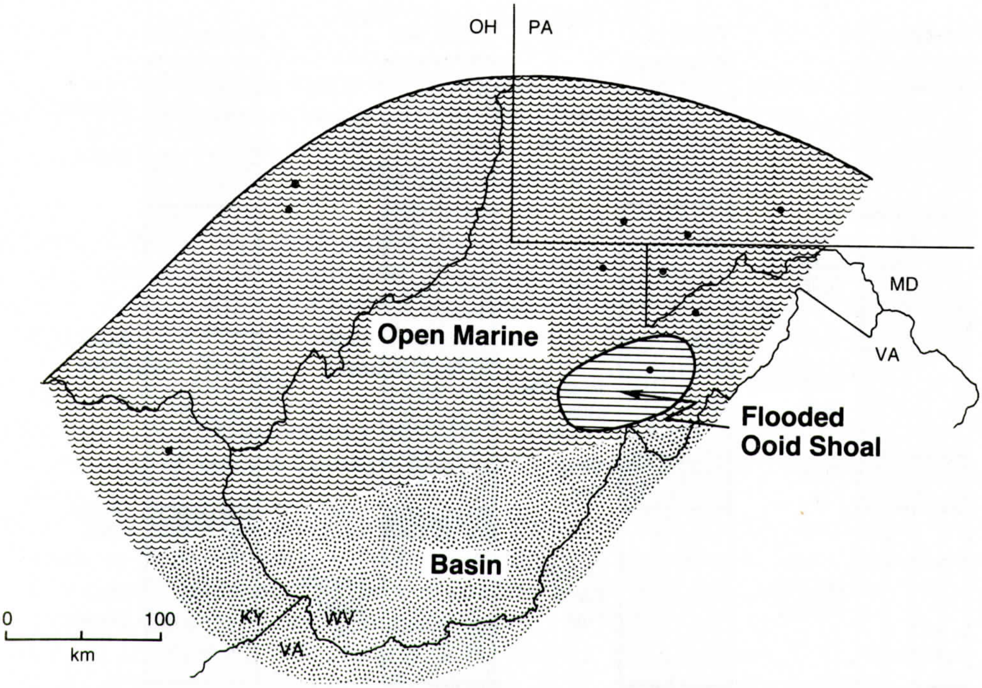

Figure 10. Paleogeography of the central Appalachian Basin following transgression of the epicontinental sea, Stage 3.

Representative sections from around the basin (Figure 11) furnish an idea of equivalent facies during Greenbrier deposition. The transgressive nature of the Greenbrier Formation is evident in every outcrop. On the western side of the basin near Carter, Kentucky, the initial coastal-sand-flat facies is overlain by tidal-flat sediments. Increasingly more open conditions are seen upwards in the section with the restricted-gulf facies followed by the open-gulf and finally open-marine facies. The same relationships are evident at the Zanesville, Ohio, locality; however, the basal sand-flat facies is missing. In north-central West Virginia at Greer, the coastal-sand-flat facies is overlain by clastic sediments deposited during the terrigenous pulse. Sediments of the open-gulf facies directly overlie the sandstones and shales. No sediments representative of tidal-flat or restricted-gulf conditions are recognized at this locality. It is possible that this section was located far enough from the shoreline that tidal-flat and restricted environments never existed there. At Canaan Valley, the section located closest to the West Virginia dome, a much different sequence of facies is seen. Fairly well-developed oolitic-shoal deposits and interbedded subtidal sediments are laterally equivalent to the coastal sand flat. Terrigenous clastic sediments overlie these oolitic deposits as at Greer. Ooid shoals again became established after the clastic influx ceased, but the oolite contains a significant clastic content. Muddy oolitic sediments of the flooded shoal cap the sequence in this area.

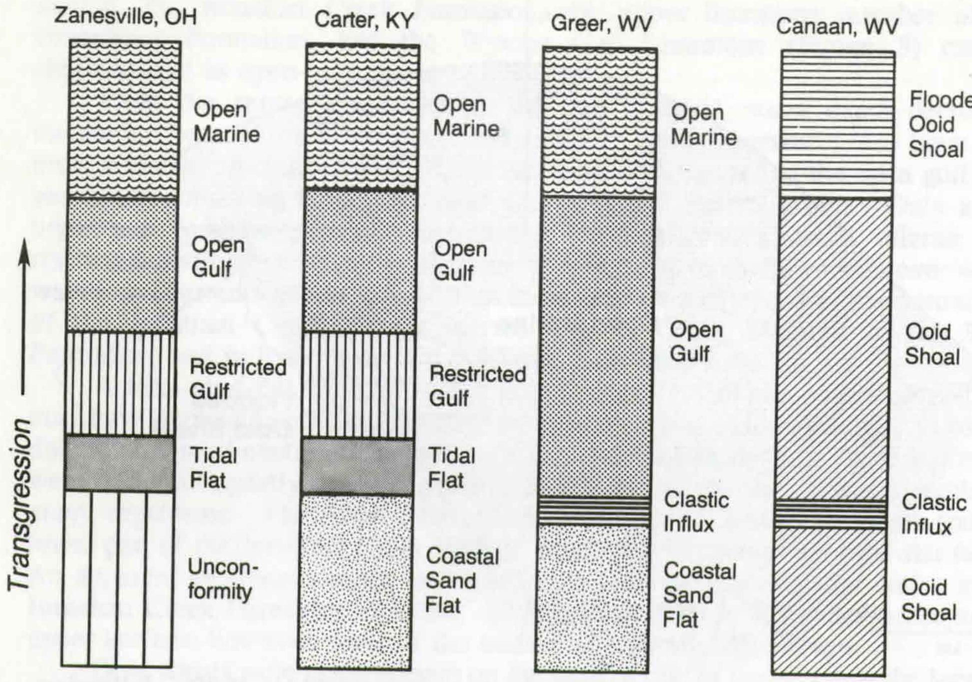

Figure 11. Schematic diagram of representative sections showing equivalent facies across the basin. Columns not to scale.

CONCLUSIONS

The Upper Mississippian Greenbrier Limestone and equivalents preserve a transgressive sedimentary sequence. A change from extremely shallow to open-marine conditions is recorded throughout the central Appalachian Basin.

The Loyalhanna-Trough Creek-Warix Run Limestone was deposited as a coastal sand flat that extended along the shoreline of the Mississippian embayment. Rejuvenation of a northern source land or reworking of older sandstones during transgression produced a flood of quartz sand that mixed with carbonate grains, forming the extensive sand flat. At the same time, ooid shoals of the Denmar Formation were being deposited on the eastern side of the basin along the hinge-line zone between shelf and basin.

The remainder of the Greenbrier Limestone consists of a deepening-upwards sequence produced during continued transgression of the epicontinental sea into the shallow gulf. Initially, open-gulf conditions were present in the central portion of the embayment where muddy skeletal sands were deposited. Shoreward of this fairly open environment, restriction of circulation became more severe and a restricted gulf characterized by burrowed muds with a few scattered skeletal grains developed. Laminated and dolomitized muds of a tidal-mud-flat complex surrounded the embayment. Ooid shoals were again present along the hinge zone. Continued transgression produced open-marine conditions throughout the basin and flooded ooid shoals near the West Virginia dome.

ACKNOWLEDGMENTS

This research was supported by a grant from Gulf Oil Company. Additional funding for field work was provided by the Chevron Oil Company.

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DISTRIBUTION OF POTENTIALLY ELEVATED RADON LEVELS IN FLORIDA BASED ON SURFICIAL GEOLOGY

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ABSTRACT

A statewide radiation survey of Florida identified eighteen counties with definite evidence of elevated radon potential. Radon gas occurrences in Florida are related to the distribution of phosphatic and other clay layers of the Hawthorn and similar geologic formations. Based on the configuration of surficial exposures and the near-surface distribution of the Hawthorn and related formations, areas of potentially elevated indoor radon levels are determined for the entire state. A series of maps provides a basis for land-use decisions and a preliminary model for site-specific investigations.

INTRODUCTION

Radon-222 is universally present in the near-surface atmosphere. Its relatively short half life and easy dispersal renders it an insignificant constituent of the air we breathe. A natural, intermediate decay product of the uranium radioactive decay series, radon is generated in varying quantitites in almost all rock formations with trace amounts or greater concentrations of uranium. Radon produced in surficial geologic formations may seep to the surface and penetrate foundations to accumulate in dwellings or other structures.

Elevated concentrations of radon in homes have been documented in a number of recent surveys (e.g., Nero *et al*,, 1986). A recent statewide survey of radon in Florida employed data from indoor radon measurements, soil gas measurements, and a number of other measurable parameters to identify eighteen counties in which evidence for potentially elevated indoor radon existed (Figure 1)(Geomet, 1988).

In recognition that certain rock types in Florida are more likely to contain appreciable amounts of uranium, the survey incorporated the type and distribution of the surficial geological formations as a contributive factor in the conclusions. Because the geographic and numerical distribution of the data was variable, however, specific configurations of areas of potentially elevated radon were only generalized, and county boundaries were used to represent units within which radon data were characterized.

We attribute the source of potentially elevated indoor radon in Florida to a limited array of related geologic formations. Based on the surficial exposure of those formations (Figure 2) and their promixity to the surface as determined from borehole logs, the distribution of areas with potentially elevated indoor radon values is delineated in a series of maps. The maps thus provide an independent preliminary model for site-specific investigations, land-use decisions, and legislative considerations.

Figure 1. Areas in Florida with definite evidence of elevated radon potential (shaded) (after Geomet Technologies, 1988).

RADON

Radon-222, a decay product of radium-226, is a colorless, odorless gas with a half life of 3.85 days. It diffuses from its original source upward through the soil cover to the surface. The decay of radon 222 yields a radiogenic isotope of lead through four short-lived (less than 27 minutes) intermediate decay products. The radiation activity, through alpha particle emission, of these decay products can be hazardous to lung tissues if they are inhaled.

The amount of radon (and radon decay products) in an enclosed structure is dependent on the rate at which it diffuses into the structure and the rate at which it is removed by ventilation, leakage, and decay. Radon can seep into a structure through floor cracks, drains, and, in time, by diffusion through semi-porous materials. The use of private well water rich in radon can release radon within a home. Although definitive relationships have not been established and many enigmatic exceptions exist, it can be expected that structures with foundations closely coupled with radon-emanating soil have the potential for higher indoor radon levels than do other structures. Many factors, such as building type and construction practices, can contribute to the degree of coupling.

Regardless of other factors, dwellings built on thick geologic formations with relatively little radioelement content should accumulate only minor amounts of radon. Similarly, surficial rocks with low permeability values may delay any upward movement of radon beyond several half-lives, thereby significantly diminishing surficial radon levels. Ultimately, the major factors that affect the amount of indoor radon in Florida are: (1) the amount of uranium in the surficial formation (and its resultant soil), (2) the depth to the radioactive formation, (3) the permeability and hydrology of the formation, and (4) the nature of the structure accumulating the radon.

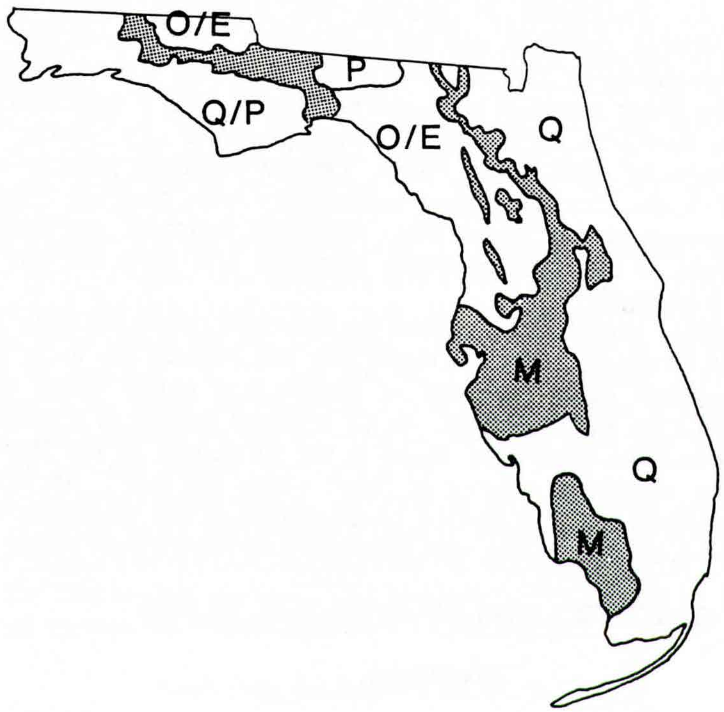


Figure 2. Generalized geologic map of Florida adapted from Puri and Vernon (1964). Key: Q: Recent and Pleistocene surface sands, marls, limestone, and shell hash; P: Pliocene sands and clays; M: Miocene sands, clays, and limestone; and E/O: Oligocene/Eocene limestones.

GEOLOGICAL RELATIONSHIP

The association of uranium with phosphatic materials in Florida and the geochemical nature of the relationship between uranium and phosphates is well-established (Altshculer et al., 1958; Espenschade, 1958; Cathcart, 1975). Uranium replaces calcium in the apatite crystal structure and remains in equilibrium with its decay products through radium. The principal phosphate deposits in Florida are located in the Miocene Bone Valley Formation of Central Florida. Phosphates in the Hawthorn and Alachua Formations in north peninsular Florida have also been mined.

The similarity of lithology among these formations and other geologic units is the basis for their inclusion in the proposed Hawthorn Group (Scott, 1988). In north Florida and south Georgia, the Hawthorn Group consists of the basal Penney Farms, Marks Head, Coosawhatchie, and Statenville Formations. Individual units are difficult to distinguish at the surface, but this grouping includes and renames the Alachua Formation (Puri and Vernon, 1964) and the various subdivisions previously proposed for the Hawthorn Formation (Brooks, 1981). In southern Florida, the Hawthorn Group is divided into the Peace River Formation, which includes the Bone Valley member among others, and the Arcadia Formation.

Throughout its distribution in Florida, the Hawthorn Group is best characterized as variable, complex, and discontinuous. The Miocene Hawthorn Formation was first named by Dall and Harris (1892) for the marine phosphatic limestones they saw being mined in north central Florida. Many redefinitions or descriptions of the Hawthorn Formation have been presented (e.g., Pirkle, 1956; Espenshade and Spencer, 1963; Scott, 1988). Despite variations peculiar to the individual formations, the Hawthorn Group sedimentary rocks generally consist of widely varying mixtures of clay, quartz sand, limestone, dolomite, and phosphate (Scott, 1988). Sand is the most abundant lithology, and clays are the most common accessory minerals.

The occurrence of phosphate throughout the Hawthorn Group has been one of the most important lithologic factors in identifying and defining the rocks of the group. The phosphates occur primarily as allochemical grains which can be divided into pelletal form and intraclasts. As the principal sources of uranium, the phosphoritic units and the many clay layers in the formations of the Hawthorn Group are the only significant sources of radon within the state. An accurate portrayal of the surface and near-surface configuration of the Hawthorn Group essentially represents a map of areas with potentially elevated indoor radon levels.

IDENTIFICATION OF POTENTIAL RADON

Distribution

The relative contribution of a soil/rock layer to the radon at the surface depends on a variety of factors, including the physical characteristics of the soil and the actual distribution of the uranium concentration with depth. Using a radon diffusion transport model developed by Bolch and reported by Roessler *et al*, (1979), the contributions of deeper layers can be estimated. Their model suggests that an "infinite" thickness is approximately 15 feet, and the first 6 feet of a uniform infinite profile contributes approximately 75% of the total surficial radon flux. However, other factors such as permeability and hydrology may serve to increase these dimensions. Groundwater absorption and subsequent movement of radon can act to deplete expected higher concentrations from some areas, but the unlikely migration of radon from groundwater into enclosing rock seems to diminish the probability of higher levels attributable to groundwater alone.

The results of this investigation were dependent on the areal distribution of the Hawthorn Group of geological formations at the surface and at depths with a cover of 50 feet or less. Each county was rated on the basis of the surficial and near-surface distribution of those geological formations characterized by appreciable concentrations of uranium. Specific subdivisions of the Hawthorn Group were assigned uranium abundance values as typified by available radioelement data.

Results of recent gamma ray spectrometry measurements as reported by

Browning and Smith (1986), Abbott *et al.* (1988), and Hansen (1988) yielded the most systematic characterizations. The originally defined Hawthorn, Alachua, and Bone Valley Formations all exhibit variable, but potentially high, concentrations of uranium and were assigned a concentration factor of "1" (more than 10 ppm). Those subdivisions of each of the formations above (all now redefined within the Hawthorn Group) with uranium concentrations typically 3-10 ppm were assigned a concentration factor of 0.5. The Inglis Formation, one of the Eocene age Ocala Group of limestone formations, was included in this category because extensive sampling and analyses of this unit revealed significant uranium concentrations and attributed them to leaching of the now-absent Hawthorn sedimentary rocks (Abbott *et al.*, 1988). All other surficial geological formations in Florida are characterized by uranium concentrations of less than 3 ppm and, accordingly, were assigned a concentration factor of 0.

Using a planimeter and a geologic map, the percentile surface coverage of the designated geologic units was determined for each county. Surface formations were identified as those with less than 10 feet of overburden. Based on descriptions of borehole cuttings (Johnson, 1986), percentile coverages were also determined at depths of 10-30 feet and 30-50 feet. Figures 3 to 6 show the configuration of the Hawthorn Group as it exists at the surface or within 30 feet of the surface. This distribution can be construed as a first order map of areas subject to potentially elevated indoor radon levels.

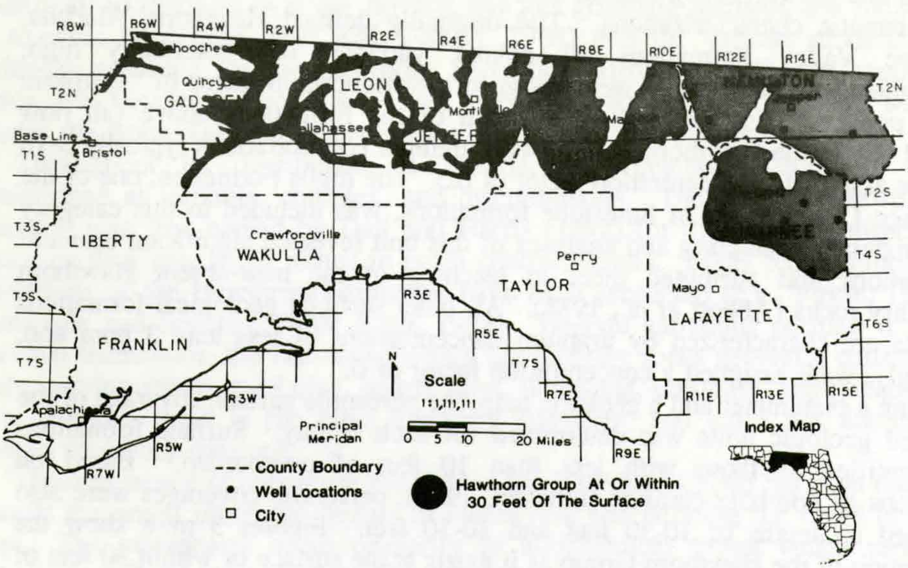
Using the relationship below, the various geologic units were assigned a weighting or depth factor universally related to depth from the surface. Finally, the relative presence of uranium-bearing material was expressed for each county in terms of the "equivalent surface", the equivalent percentage of surface area characterized by uranium concentrations exceeding 10 ppm.

$$\text{Equivalent Surface} = \text{Sum of } (A_i D_i C_i)$$

where A_i = % of county area represented by the ith geologic unit
D_i = depth factor for the ith geologic unit
with $D = 1$ for surface occurrence,
$D = 0.75$ for 10-30 feet occurrence,
and $D = 0.25$ for 30-50 feet occurrence.
C_i = concentration factor for the ith geologic unit
with $C = 1$ for >10 ppm,
$C = 0.5$ for 3-10 ppm,
and $C = 0$ for <3 ppm.

Table 1 and figure 7 present the results of this exercise. The similarity to the results from the spot-sampling and composite-factor analyses (Figure 1) is evident, but the configuration of delineated areas with potentially elevated radon (Figures 3-7) presents a new dimension for land-use issues by defining counties that have high, moderate, and low risks of radon concentrations.

This method is useful because it grades areas on the distribution of the probable source of uranium, rather than a reliance on minimal sampling densities or results. It provides a rapid general assessment of an area based on the expectations of geological distributions without detailed field sampling.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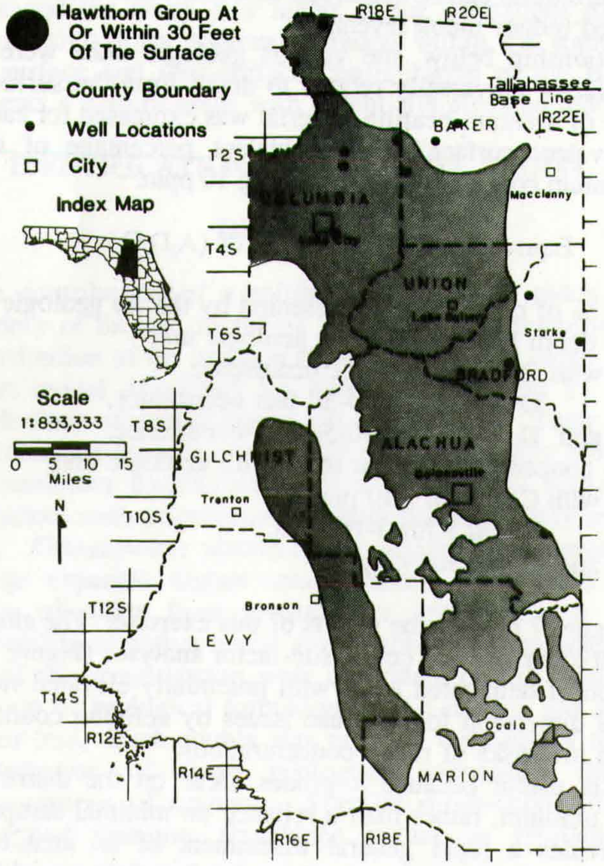
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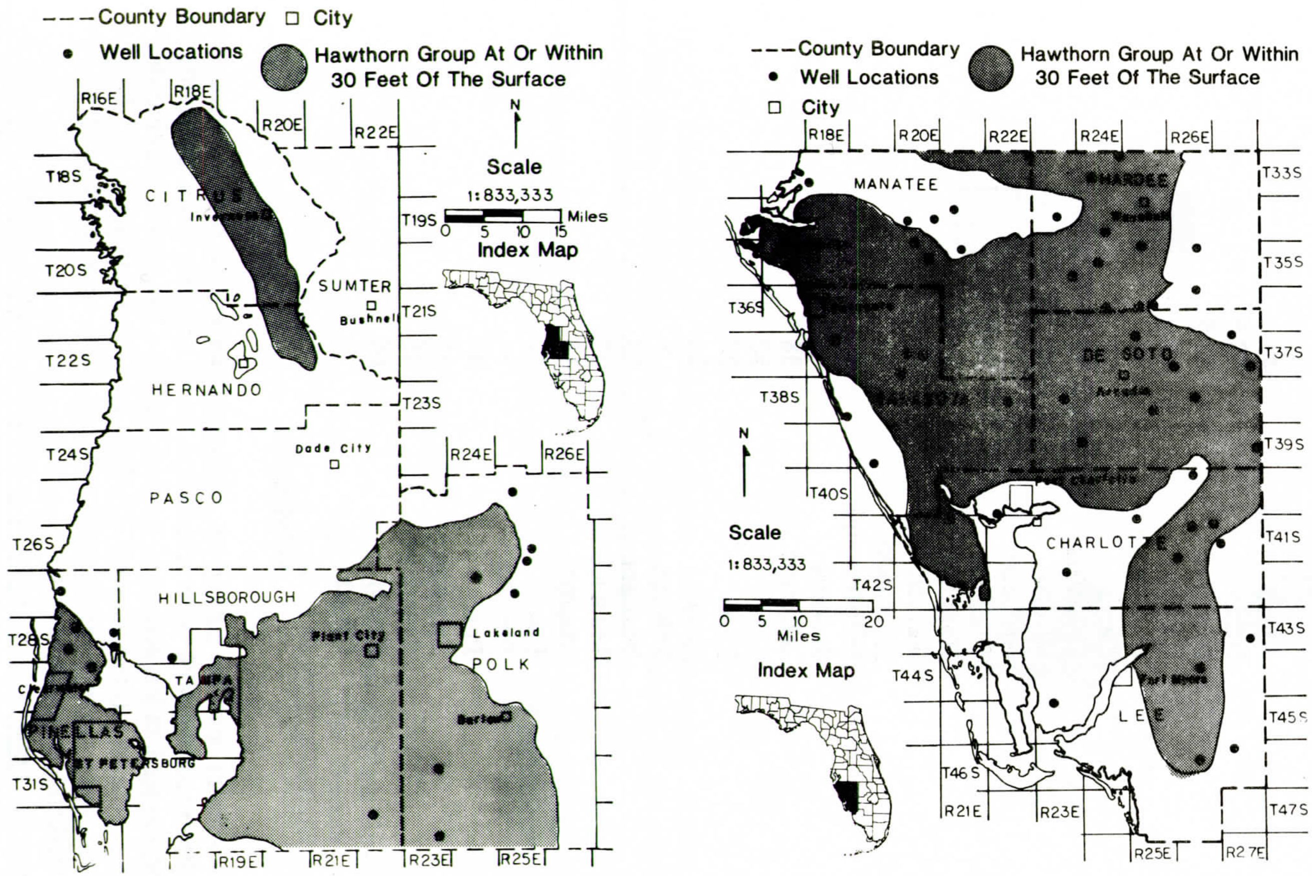

Figures 3-6. Distribution of surficial and near surface exposures of the Hawthorn Group as an indicator of potentially elevated indoor radon levels. Well locations depict sources of data used for depth evaluation.

Table 1. Equivalent Surface Area of Hawthorn and Related Geologic Formations

County	Percent Area
Alachua	49
Baker	20.5
Bradford	31.5
Calhoun	10
Charlotte	30
Citrus	34
Columbia	53
Desoto	65
Gadsden	37
Gilchrist	10.5
Hamilton	53
Hardee	53
Hernando	14
Hillsborough	60
Jackson	7
Jefferson	38
Lee	32
Leon	27
Levy	21
Liberty	5
Madison	63
Manatee	51
Marion	15
Pasco	12
Pinellas	34
Polk	44
Sarasota	51
Suwannee	18
Union	65
Others	0

SUMMARY

Those counties with an equivalent surface of designated high concentration geologic units exceeding 40% were considered, on an arbitrary basis, as having the potential for elevated radon and were labeled "high". The grade "medium-high" was used for equivalent surfaces of 25-39%, and "medium-low" for 10-24%. Those counties with an equivalent surface below 10% were considered to have "low" potential indoor radon levels.

The specific depiction of zones of potentially elevated indoor radon levels will require, of course, an exhaustive accumulation of directly-measured radon data. The uncertain relationships among indoor radon levels, construction practices, and land modifications will continue to relegate areas identified with significant radon concentrations as merely those with a potential to yield elevated

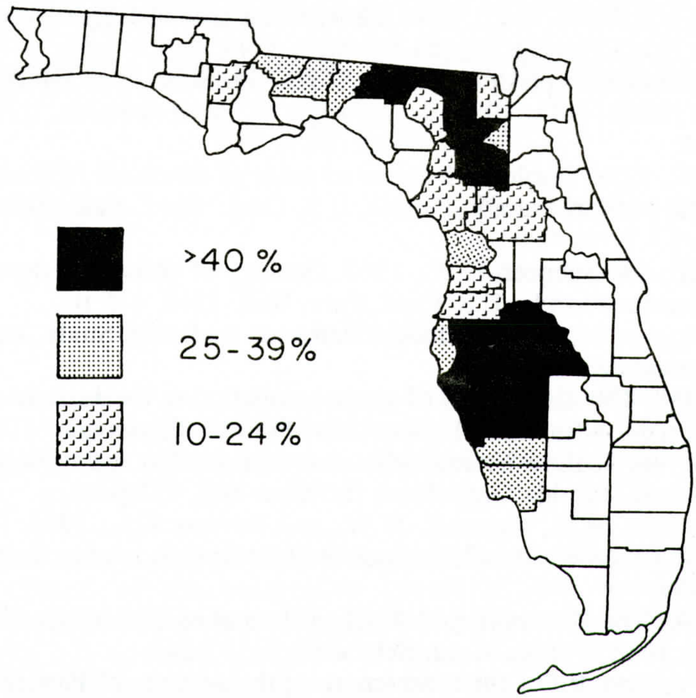

Figure 7. Distribution of Florida Counties with Equivalent Surface Areas exceeding 10%. Equivalent surface is the equivalent percent of the surface area with concentrations of uranium greater than 10 ppm.

indoor radon accumulations. Nevertheless, site-specific investigations should be initiated only after geological constraints are determined and preliminary mapping is pursued.

ACKNOWLEDGEMENTS

This investigation was initiated under a research contract from Geomet, Inc., with the University of Florida Radon Task Force. The Bureau of Mine Reclamation, Division of Natural Resources, State of Florida, generously provided Hansen with an internship to support this work.

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A SUB-RECTANGULAR PALEOVALLEY SYSTEM, CASEYVILLE FORMATION, EASTERN INTERIOR BASIN, WESTERN KENTUCKY

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ABSTRACT

Facies analysis of outcrops and more than 600 subsurface logs in a three-county area of western Kentucky indicate the existence of a sub-Pennsylvanian paleodrainage system at the base of the Caseyville Formation, herein named the Indian Lake paleovalley system after exposures near Indian Lake, Hancock County.

The paleovalley system is developed on horst blocks of the Owensboro Graben. Control of the paleovalley system by the Waitman-Griffith and Knottsville fault zones is indicated by (1) channeling on the horst blocks bounded by the faults, (2) complex structural contours on the base of the Caseyville Formation parallel and perpendicular to faulting, reflecting an approximately rectangular drainage pattern, (3) paleocurrent indicators parallel to faulting, and (4) a paleocolluvial deposit along a fault-bounded valley wall.

Planar and trough crossbedded, pebbly, quartz litharenites were deposited within the aggrading, fault-bounded, bedrock valleys by low-sinuosity, multi-channel streams.

INTRODUCTION

Analysis of the sub-Pennsylvanian unconformity in the Eastern Interior Basin is important because of the history of hydrocarbon reserves along the unconformity and because of what the unconformity reveals about the controls on sedimentation during the mid-Carboniferous.

During the Early Pennsylvanian Period, and perhaps originating in the Late Mississippian Period, a series of subparallel, alluvial valleys crossed the Eastern Interior Basin (Figure 1), creating an unconformity beneath the Pennsylvanian rocks (Bristol and Howard, 1971). In the northern part of the basin, paleovalleys cross fold axes with little diversion, and there is little coincidence of paleovalley position with fault trends, so it was assumed that there was little structural control of paleovalley position (Bristol and Howard, 1971, 1980). The purpose of this study is to illustrate that there is significant coincidence of paleovalley position with fault trends in the southeastern part of the basin and that there was apparent structural control of the unconformity.

Previous Investigations

For many years investigations of the sub-Pennsylvanian drainage network of

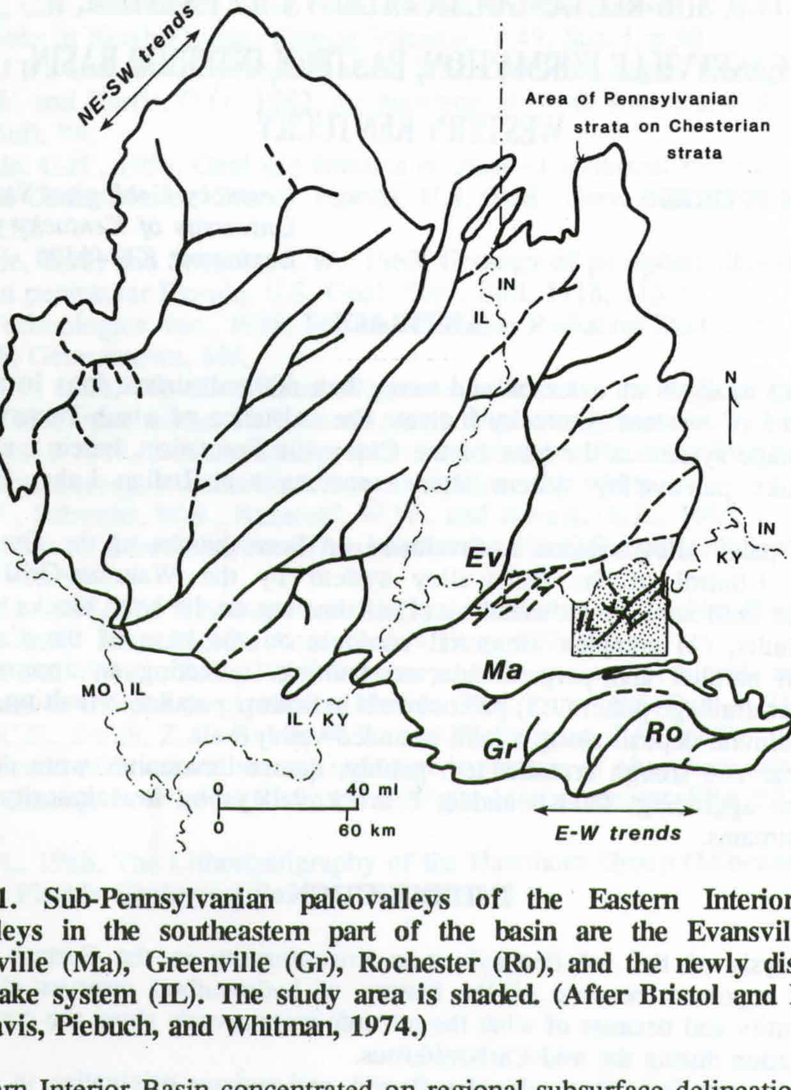

Figure 1. Sub-Pennsylvanian paleovalleys of the Eastern Interior Basin. Paleovalleys in the southeastern part of the basin are the Evansville (Ev), Madisonville (Ma), Greenville (Gr), Rochester (Ro), and the newly discovered Indian Lake system (IL). The study area is shaded. (After Bristol and Howard, 1971; Davis, Piebuch, and Whitman, 1974.)

the Eastern Interior Basin concentrated on regional subsurface delineation of the major paleovalleys, and more recently on detailed sedimentological studies of the paleovalley fill along the exposure limit of Pennsylvanian rocks in the basin (Shiarella, 1933; Siever, 1951; Wanless, 1955; Potter and Desborough, 1965; Bristol and Howard, 1971, 1980; Davis and others, 1974; Sedimentation Seminar, 1978). These investigations showed that there was a considerable unconformity beneath the Pennsylvanian rocks, highlighted by a series of major paleovalleys and secondary paleochannel networks incised into the sub-Pennsylvanian bedrock as much as 140 meters.

Location and Geologic Setting

The study area is north of the Madisonville Paleovalley of Davis and others (1974), in parts of Daviess, Ohio, and Hancock Counties (Figure 2). On previous maps (Bristol and Howard, 1971) the study area was considered part of the Madisonville Paleovalley (Figure 1). However, subsurface mapping of the three counties, utilizing more than 600 subsurface records, indicates that channeling in the study area is distinctly separate from the Madisonville Paleovalley to the south and has a distinctly different erosional pattern from the Madisonville Paleovalley.

The basal Pennsylvanian strata in the study area are part of the Caseyville Formation, which ranges in thickness from 59 to 152 meters, and is thickest in the paleovalleys. In the study area the Caseyville disconformably overlies Chesterian marine carbonates, sandstones, and shales (Figure 3).

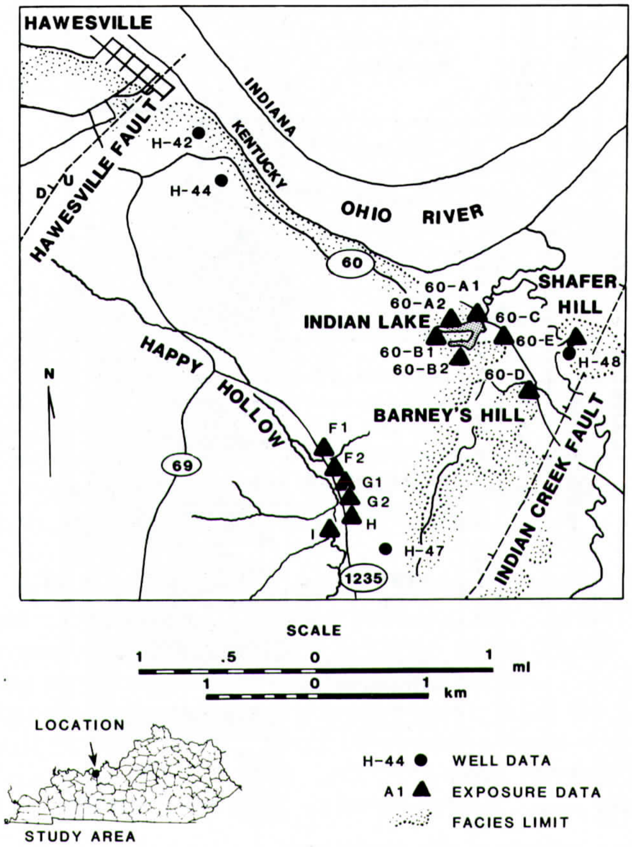

Figure 2. Location map of paleovalley-fill outcrop exposures at Carter coordinate location Q-34, Hancock County, Kentucky. This area is in the northeasternmost part of the study area, outlined on Figures 1, 5, 6, and 7.

Tectonic Setting

The Eastern Interior Basin originated as an aulocogen formed during the Precambrian or Early Cambrian, followed by development of an interior cratonic sag basin (Braile and others, in press; Trask and others, in press). The aulocogen is called the Reelfoot Rift. It is a triple- (Braile and others, in press) or double-branched (Eidel and others, in press) rift that has periodically affected erosion and sedimentation in the Eastern Interior Basin from the time of its inception to the present.

Between the two principal arms of the aulacogen are a series of smaller grabens. One of these is the Owensboro Graben (Sanders, 1984). The Owensboro Graben is bounded by northeast-southwest-trending normal faults (parallel to the Southern Indiana Arm or Wabash Valley trend) and is bordered (or truncated) on the southwest by the Rough Creek Graben (Figure 4).

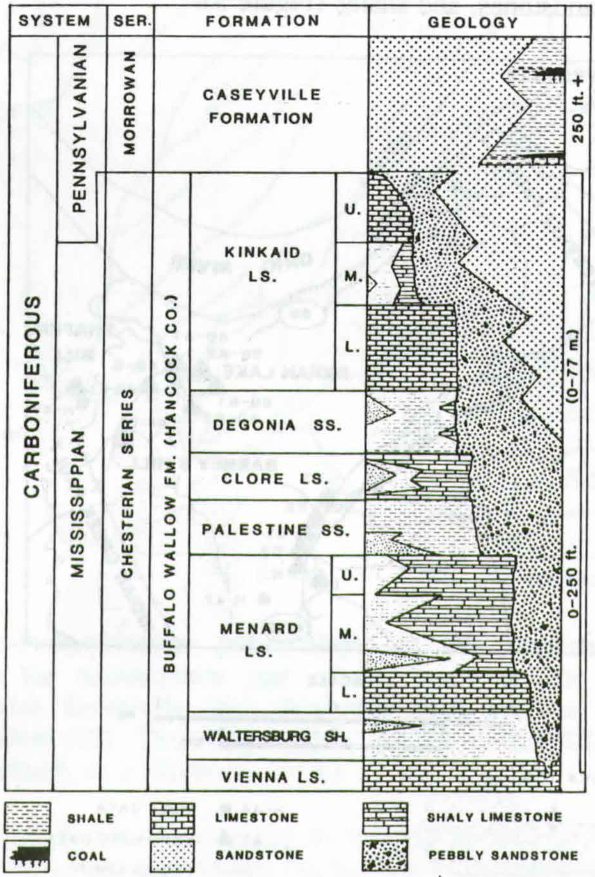

Figure 3. Geologic column of the study area.

PALEOVALLEY PATTERN

The uppermost mappable Chesterian carbonate in the study area not completely truncated by channeling in the Caseyville Formation is the Vienna Limestone (Figure 3). The Vienna is a common subsurface marker in the basin because it is easily recognized on geophysical logs. A structure map on the top of the Vienna Limestone (Figure 5) indicates a consistent dip to the west. This dip is similar to that of other Chesterian subsurface horizons in the study area.

A structure map on the top of the uppermost, preserved Chesterian rocks and the base of the Caseyville Formation (Figure 6) also indicates a westward dip;

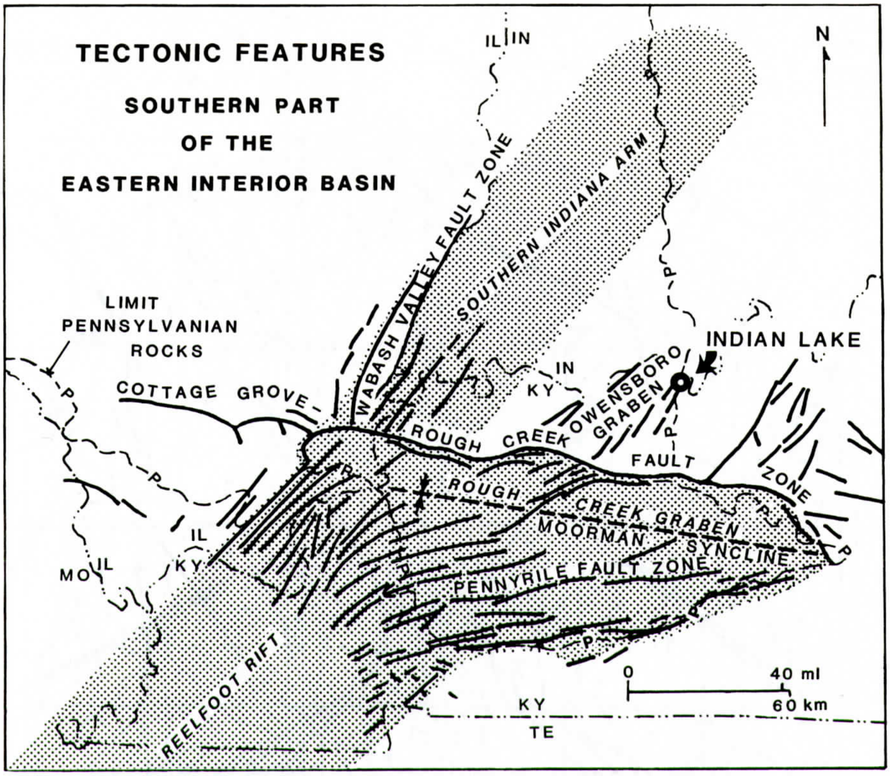

Figure 4. Tectonic features of western Kentucky (after Sanders, 1984; Braile and others, in press; Trask and others, in press).

however, the surface is extremely irregular. Greatest elevation differences occur subparallel and perpendicular to faults bounding the Owensboro Graben. A paleogeologic map on the top of the Chesterian rocks (Figure 7) illustrates the trend of missing section on the sub-Pennsylvanian surface. The pattern shows (1) a slightly higher percentage of missing section on the horst blocks than within the graben, (2) at least four parallel trends of missing section coincident with fault trends in the Knottsville Fault Zone, and (3) several trends of missing section perpendicular to fault trends in the Knottsville Fault Zone.

PALEOVALLEY-FILL SEDIMENTS

Indian Lake Pebbly-Sandstone Facies

In the northeastern part of the study area the basal Pennsylvanian, conglomeratic member of the Caseyville Formation, mapped by Bergendahl (1965) and found to be disconformable with underlying formations of the Chesterian Series to depths of 65 meters, is exposed in roadcuts and bluffs near Indian Lake, Hancock County (Figure 2). The member thins to the west near the Hawesville Fault, and is bounded on the east by the Indian Creek Fault (Figure 8).

At location 60-E (Figure 2) the basal contact of the Caseyville formation is

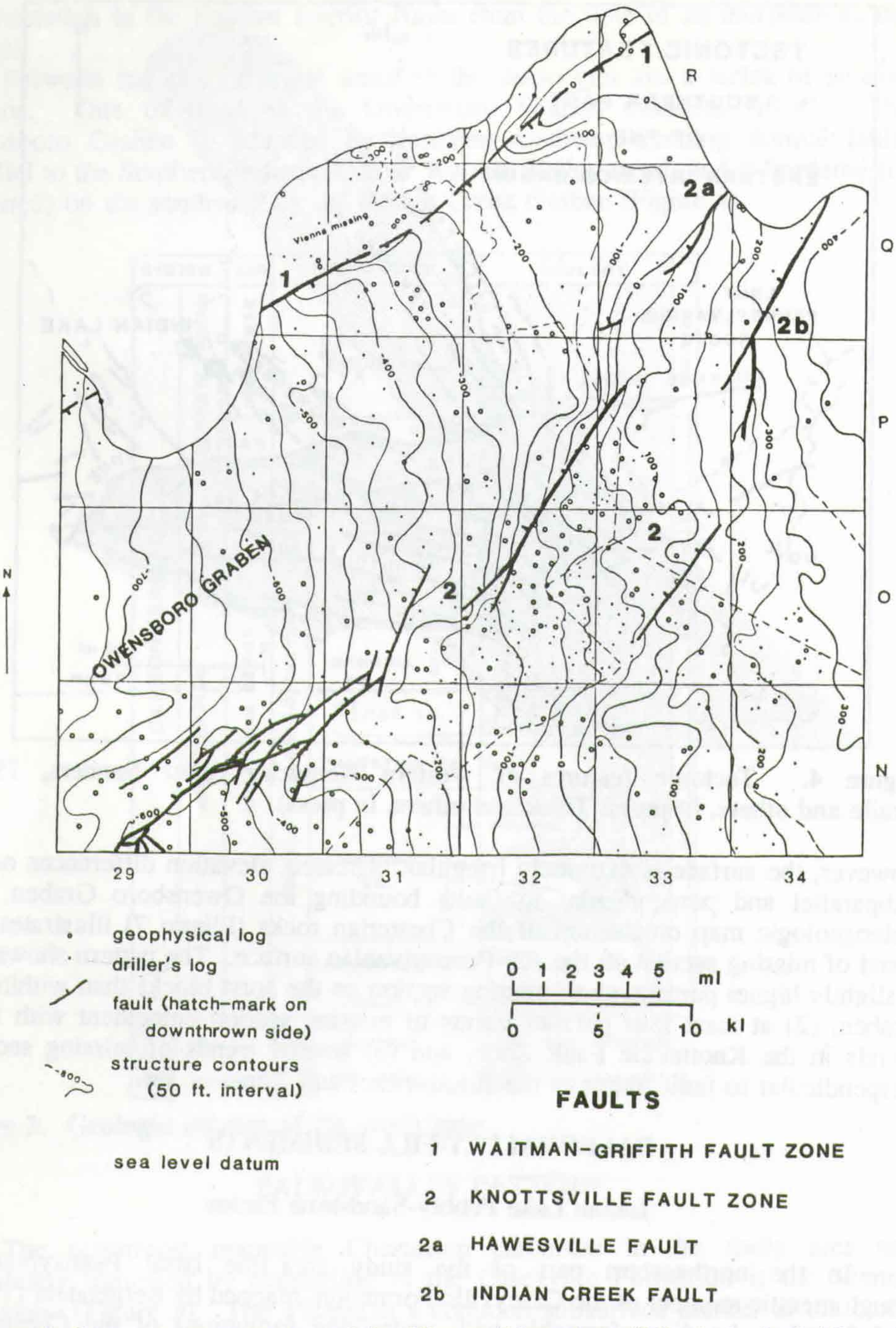

Figure 5. Structure map on top of the Vienna Limestone (Mississippian). Note the general westward dip of this Chesterian marker horizon.

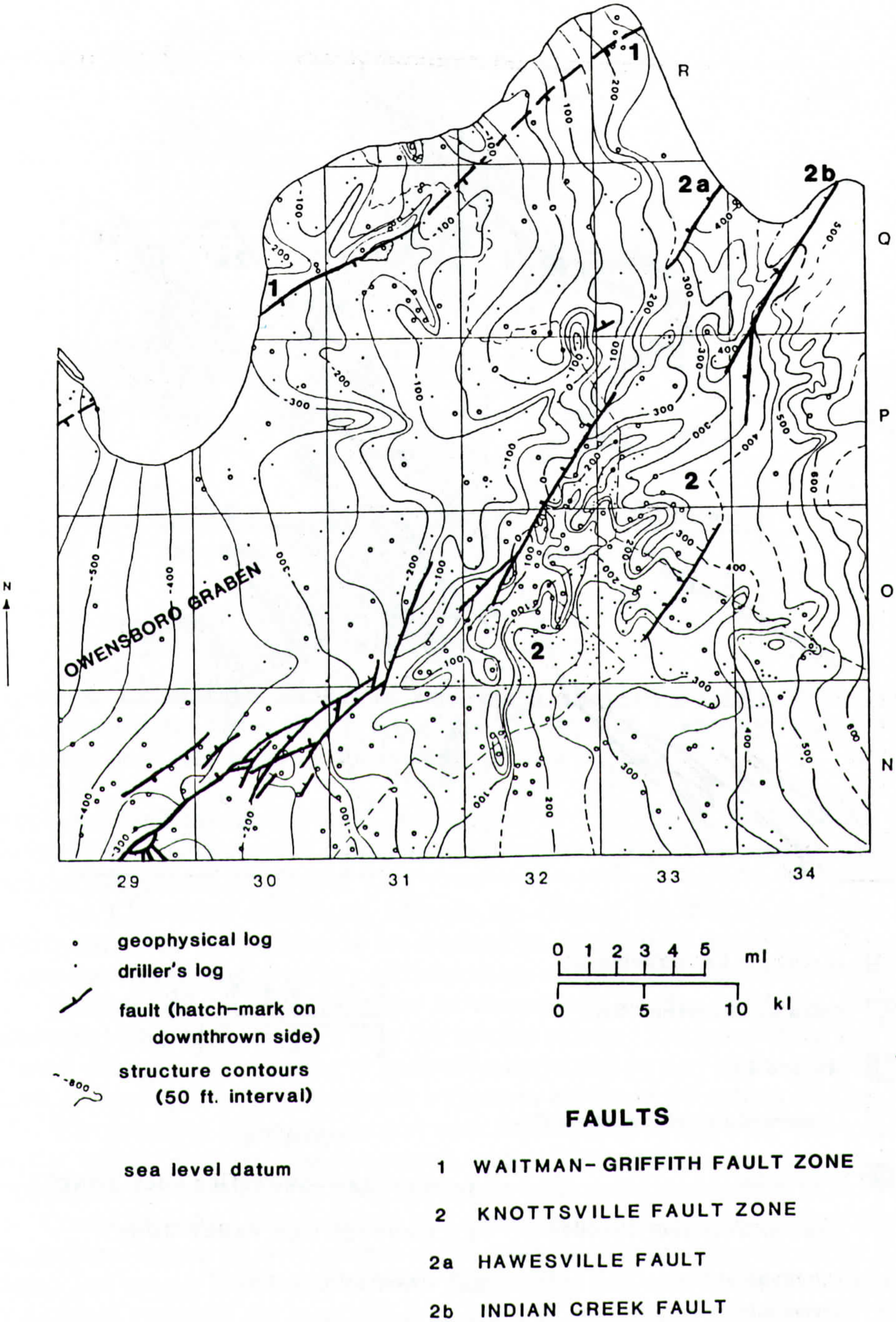

Figure 6. Structure map on top of the uppermost Chesterian rocks, marking the contact between the Mississippian and Pennsylvanian Systems. Note the irregular structural surface, especially on the horst blocks of the Owensboro Graben.

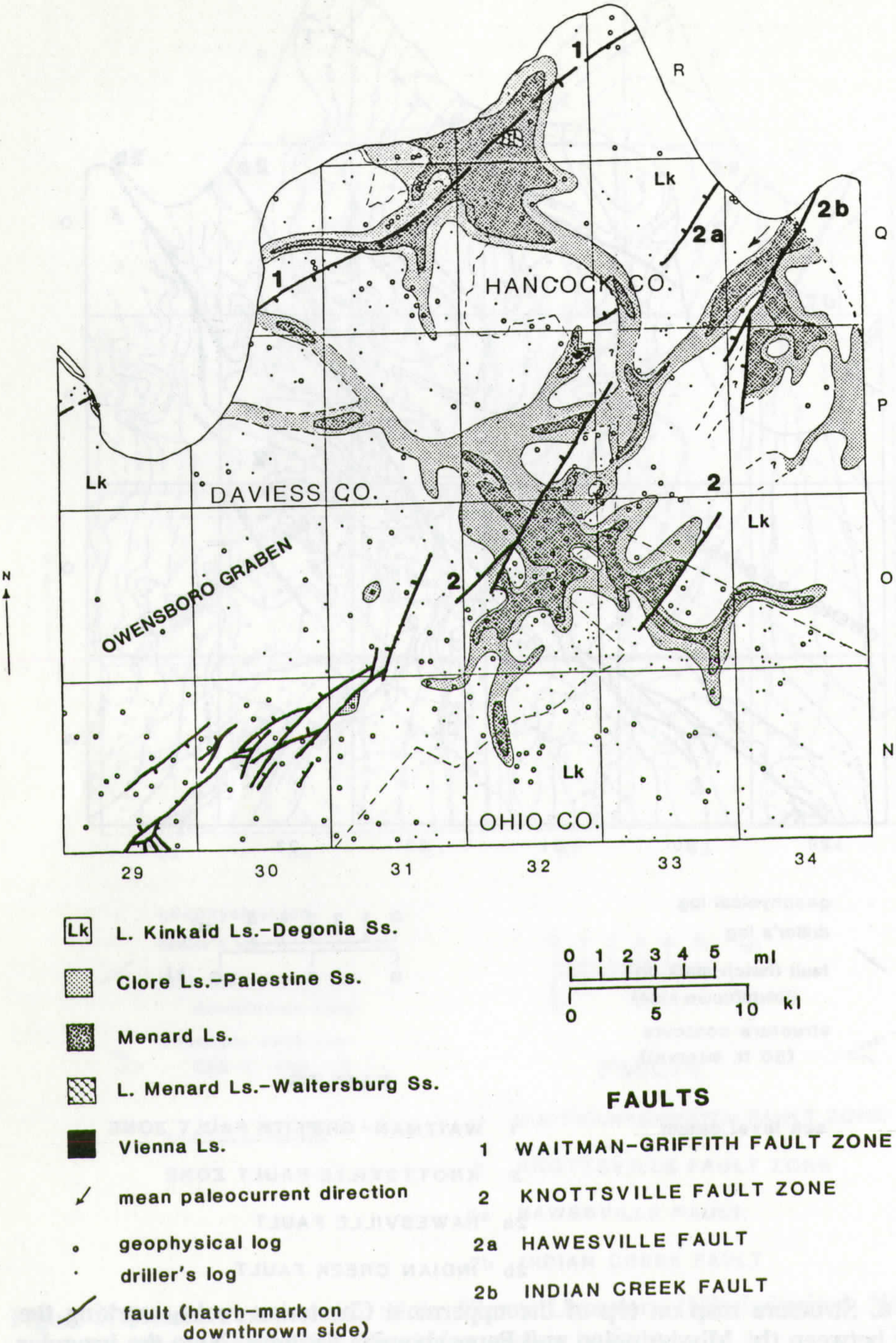

Figure 7. Sub-Pennsylvanian paleogeologic map showing the uppermost preserved Chesterian strata beneath Pennsylvanian rocks. Note the sub-rectangular pattern of missing section.

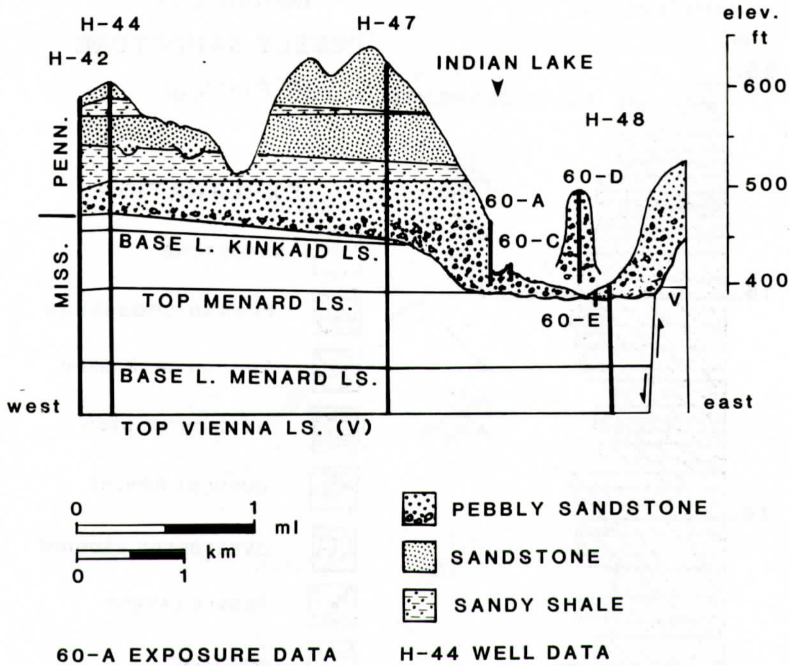

Figure 8. Generalized section of the Indian Lake paleovalley. Note that the pebbly-sandstone facies fills a broad paleovalley that is steeply walled along a bounding fault (see Figure 2 for location of data points).

poorly exposed in a small-scale channel that is 5 meters across and less than 2 meters deep. Channel fill consists of fine-grained, ripple-laminated and planar crossbedded sandstone (Figure 9).

The Chesterian carbonates beneath the contact are divided into two zones (Figure 9). The upper zone is an arenaceous, brecciated, intraclastic, bioclastic grainstone, containing a variety of brecciated, micritic, and carbonate grains.

Detrital quartz grains (similar in mineralogy to the overlying Caseyville sandstone) commonly occur within the breccia cracks. The lower zone is a fossiliferous, dolomitic wackestone to packstone correlated to part of the Menard Limestone, indicating missing Chesterian section in excess of 36 meters (Figure 9).

The principal valley-fill section near Indian Lake consists of buff to yellow, poorly sorted, fine- to coarse-grained, quartz litharenites with common quartz pebbles, herein informally termed the Indian Lake pebbly-sandstone facies (Figure 9). Cosets of planar crossbedding and small-scale trough crossbedding dominate the section (Figure 9), with current-ripple cross lamination common on the tops of planar and trough crossbedded units. Convoluted and overturned bedding occurs in a planar crossbed set marginal to a small (1 m), trough crossbedded channel. The tops of beds are overturned in the direction of transport.

The sequence at Indian Lake generally fines upward, although variation in grain size is greater within individual cross sets than between sets. Most cosets fine upward, and some cosets show thinning and fining upward- sequences on the order of 1 meter thick (Figure 9). Grain size ranges from fine sand (1/8 mm) to

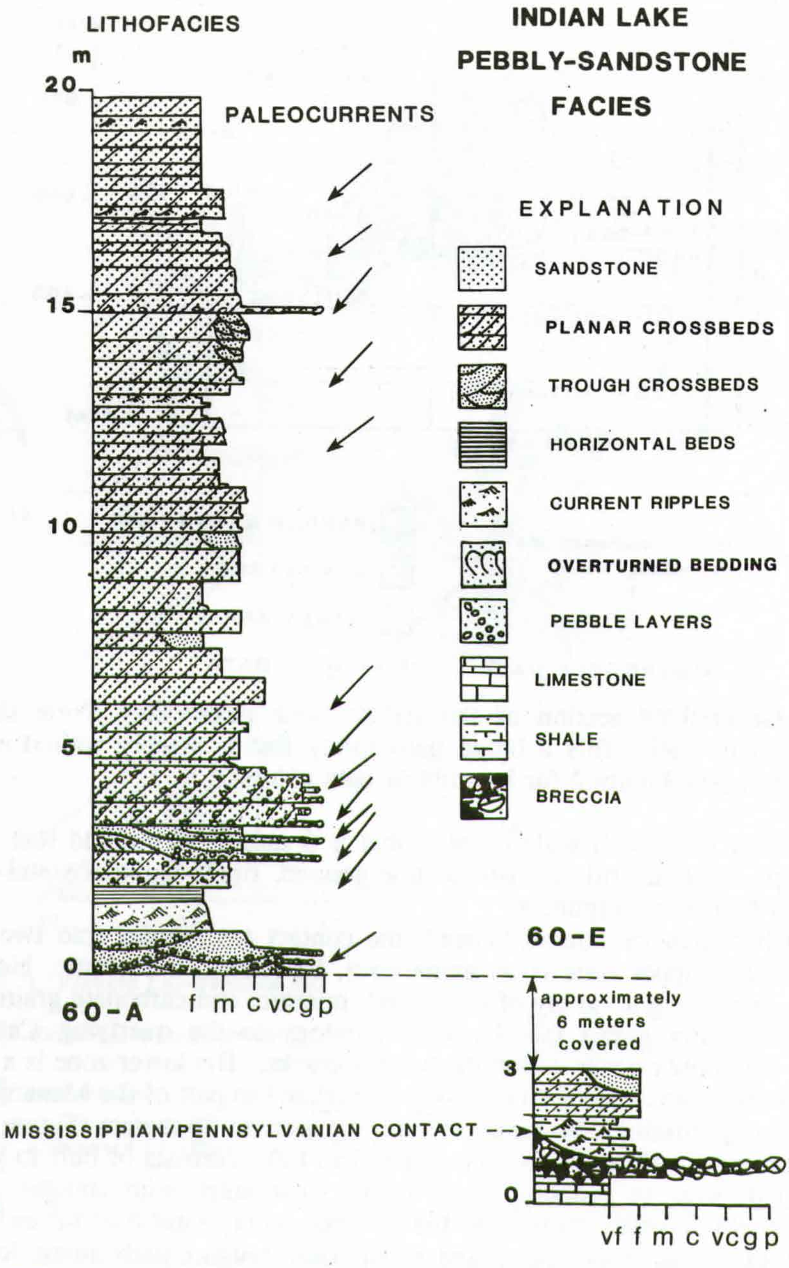

Figure 9. Measured sections of the Indian Lake pebbly-sandstone facies (see Figure 2 for location of sections).

coarse-pebble gravel (24 mm), with an average grain size of medium- to coarse-grained sand (0.25 to 0.50 mm). Quartz pebbles occur above and beneath bedding-plane surfaces, and along foresets. Commonly, pebbles occur in layers a single pebble in thickness. Pebbles are most abundant in the lower 5 meters of the section (Figure 9).

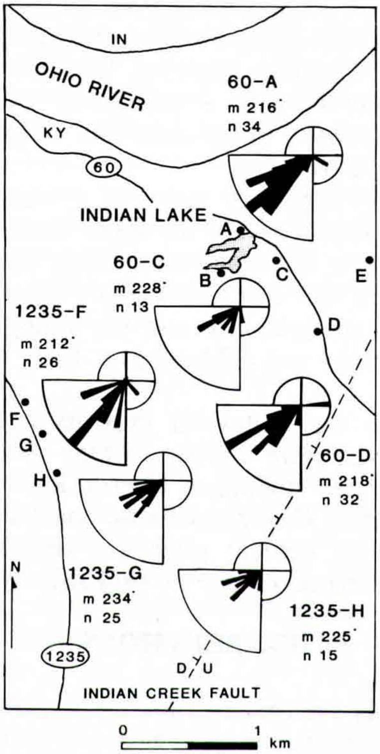

Figure 10. Paleocurrent measurements of the Indian Lake pebbly-sandstone facies (m = mean, n = number of measurements).

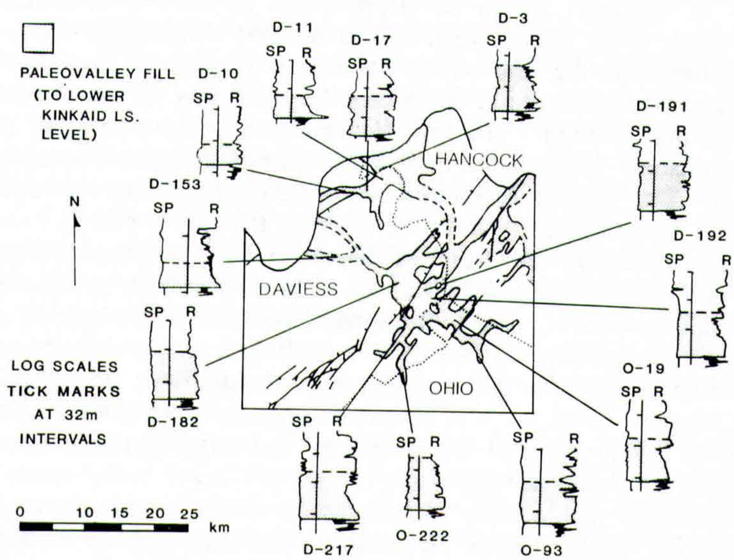

Figure 11. Typical induction-electric logs, Indian Lake Paleovalley.

Paleocurrent directions of crossbedding from 79 measurements along U. S. Highway 60 indicate a mean average paleocurrent direction of S 38° W, with a median of S 52° W. Along Kentucky Highway 1235, 68 measurements indicate the mean direction is S 43° W, with a median of S 52° W. In all areas, paleocurrent direction is unimodally to the southwest and parallel to the bounding Indian Creek Fault (Figures 9, 10).

The Indian Lake pebbly-sandstone facies is overlain by the more typical clays, shales, siltstones, and sandstones of the upper Caseyville Formation. Fine- to medium-grained sandstone is common, with pebbly sandstones becoming rare and discontinuous. Locally, a thin coal bed occurs a few meters above the valley fill (Bergendahl, 1965). Coal beds also cap the valley fills in the Rochester Paleovalley to the south (Shawe and Gildersleeve, 1969; Sedimentation Seminar, 1978).

South of Indian Lake the valley-fill deposits occur in the subsurface. Subsurface lithologies (derived from drillers' records and geophysical logs) vary from sandy shale to sandstone. Induction electric log responses for valley-fill sandstones in Ohio and Daviess Counties indicate sharp contacts with underlying Chesterian strata. Typically, vertical grain-size trends are indistinct in the sandstones, although some sandstones fine upward slightly (Figure 11).

INTERPRETATIONS

The Indian Lake pebbly-sandstone facies contains no marine indicators. In addition, the facies (1) is conglomeratic, (2) is poorly sorted, (3) is dominated by planar and trough crossbedding, (4) has unimodal paleocurrent indicators, (5) has a sharp erosional base, (6) is apparently lacking in laterally associated, fine-grained overbank deposits, and (7) is elongate in geometry, with paleocurrent indicators oriented down-dip and parallel to the axis of elongation. This combination of characteristics is common in fluvial depositional environments (Pettijohn and others, 1973; Cant, 1982; Friena, 1982; Galloway and Hobday, 1983).

Cross sections of the Caseyville sandstone (Figure 8) indicate that the aggrading streams occupied a fault-bounded valley that was cut into the underlying Chesterian carbonate section. The low dispersion of paleocurrents in the Indian Lake pebbly-sandstone facies (Figures 9, 10) indicates that the streams were low-sinuosity types. The paucity of continuous outcrops precludes definition of the types of channel pattern (Harms and others, 1982; Bridge, 1985).

The general fining-upward trend of the lower 10 to 15 meters of the Indian Lake pebbly-sandstone facies indicates deposition possibly as coarse-grained channel fill or a channel bar. Concentrations of pebbles on the tops of crossbeds may represent the preservation of armored bars (Baker, 1984). Overturned planar beds attest to rapid deposition and possibly to a change from flood peak to non-flood stages (Weimer, 1976, p. 32). Rapid changes in velocity and depth are also inferred from the preservation of fining-upward and thinning sequences of planar crossbeds capped by ripple laminations.

The small-scale sedimentary structures in the channel along the basal contact at location 60-E (Figure 9) indicate that this was a minor channel significantly different from the larger channels at Indian Lake. It may represent a secondary channel or chute formed during the waning stages of flooding in an otherwise bed-transport system. The channel is cut into the Chesterian Menard Limestone and a highly brecciated carbonate zone (Figure 9). Because of the (1) brecciation of clasts indicative of subaerial exposure, (2) wide range of clasts indicating transport from several different Chesterian horizons, (3) detrital sand grains that are mineralogically similar to the overlying Caseyville sandstones within breccia cracks, and (4) position of the zone along the eastern wall of a steep-sided fault-bounded valley, the breccia zone is interpreted as a paleocolluvium deposit that formed during weathering of the paleovalley walls. Possibly, the colluvium was derived from an escarpment along the bounding Indian Creek Fault. During valley aggradation, minor channels were scoured into the colluvium bank, only to be buried by fluvial sand bars.

DISCUSSION

Shawe and Gildersleeve's (1969) much smaller, complex drainages on the flanks of the Brownsville (now Rochester) Paleovalley (Figure 1) share similarities with the Indian Lake system. They compared the multichannel drainages to the modern-day Rio Caroni of South America. The complex pattern of the Rio Caroni resulted from transitional patterns of flow during humid climatic conditions, in which water attempted to carve a trunk channel through a region that previously had an arid climate with indistinct drainage patterns (Garner, 1966).

The complex pattern of the Indian Lake and surrounding paleochannel systems is similar to the multichannel drainages described by Shawe and Gildersleeve (1969). If the Rio Caroni model is applied regionally, as suggested by Howard (1969), the complexity of the Indian Lake channels can be viewed in context with the much larger Evansville Paleovalley to the north and west. According to the model, the Evansville Paleovalley is inferred to represent a large channel belt resulting from cyclic phases of transitional drainage under variable climatic conditions similar to the Rio Caroni, with the Indian Lake system representing a transitional, multi-channel drainage on the flanks.

Application of the Rio Caroni, climatically-controlled drainage model to the basin is supported by recent evidence suggesting semi-aridity and climatic variation in the Eastern Interior Basin during the Late Mississippian and Early Pennsylvanian. Multiple climatic changes, inferred from global marine shelf-fauna extinctions and paleobotanical data, resulted in cyclic transgressive/regressive episodes that affected broad expanses of low-lying coastal shelves such as those that existed in the Eastern Interior Basin (Howard, 1969; Cecil and others, 1985; Donaldson and others, 1985; Phillips and others, 1985; Ross and Ross, 1985; Heckel, 1986; Trask and others, in press). Climatic changes may have been related to changes in the shape of ocean basins, rising highlands near the equator, continental glaciation, or changing oceanic temperatures (Sloss, 1979; Ross and Ross, 1985; Rowley and others, 1985).

The lack of karst features in the carbonates beneath the Caseyville and the brecciated clasts below the channel at Indian Creek indicate non-humid conditions during the development of the unconformity, but they do not suggest aridity either. Rather, at Indian Lake the major controls appear to have been structural, as inferred from (1) incisement of channels on horst blocks of the Owensboro Graben, (2) multiple trends of channeling parallel to faulting, and (3) multiple trends of channeling perpendicular to faulting. Also, the Evansville Paleovalley (west of the Indian Lake system) follows the axis of the Southern Indiana Arm of the Reelfoot Rift, much as the pre-glacial Michigan River system has been shown to have done (Potter, 1978). This alignment suggests that tectonics of the interior sag basin may have played a significant role in the development of the Carboniferous drainage system.

Degradation of the Indian Lake and surrounding paleovalleys was probably initiated by a base-level drop following Chesterian mixed carbonate/clastic deposition. Reactivation of normal faults along the rift could have accentuated the base-level drop and entrenched streams coincident with a fault-controlled topography, or entrenchment might have followed preexisting joint patterns (related to tectonic stresses) in the Chesterian carbonates, similar to modern-day bedrock systems in Katherine Gorge, Australia (Baker, 1984).

Coincidently, Bristol and Howard's (1971) investigation indicates an area of similar complexity on the western horst of the Owensboro Graben (Figure 12). These complex drainages were probably connected across the graben. At Indian Lake, paleocurrents indicate that streams within the valley flowed to the south, yet the valleys apparently do not connect to any of the southern drainages. Hence,

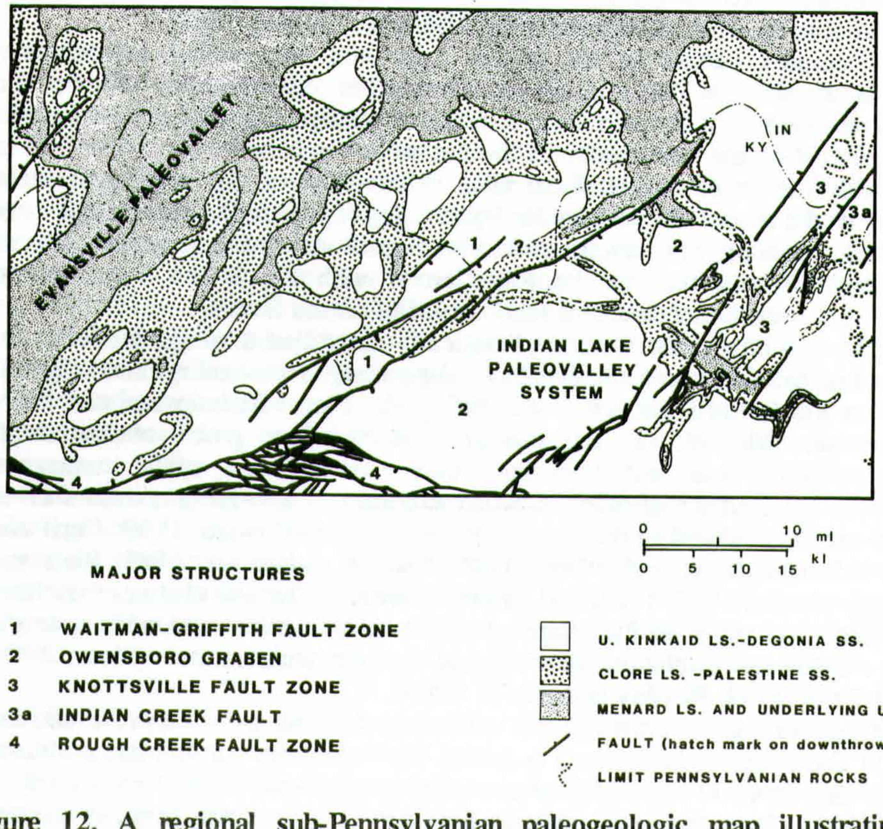

Figure 12. A regional sub-Pennsylvanian paleogeologic map illustrating the position of the Indian Lake system and other secondary, complex channel networks on the flanks of the Evansville Paleovalley (Evansville Paleovalley as mapped by Bristol and Howard, 1971).

flow probably was diverted through the complex drainages to the west, where they drained into the much larger Evansville Paleovalley.

Eustatic or tectonic base-level changes also affected valley aggradation, causing valley backfilling, as evidenced by the widespread deltaic sedimentation that caps the valleys throughout the basin (Davis and others, 1974; Sedimentation Seminar, 1978). During backfilling, it might be expected that the entire range of deltaic-margin environments, including estuarine conditions, affected valley filling, but as of yet these have not been documented in the Indian Lake system.

ACKNOWLEDGMENTS

I gratefully acknowledge the comments and suggestions of John S. Bridge and Robert C. McDowell, who reviewed the manuscript for publication. I would also like to thank the reviewers at the Kentucky Geological Survey, including Margaret L. Smath, John D. Kiefer, James C. Cobb, and Donald C. Haney, for their comments and encouragement. Finally, I would like to thank those people who advised me during the course of the investigation and who helped in collecting the data: Russell G. Sheperd, Frank R. Ettensohn, John C. Ferm, Jack Pashin, and Donald Brice.

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